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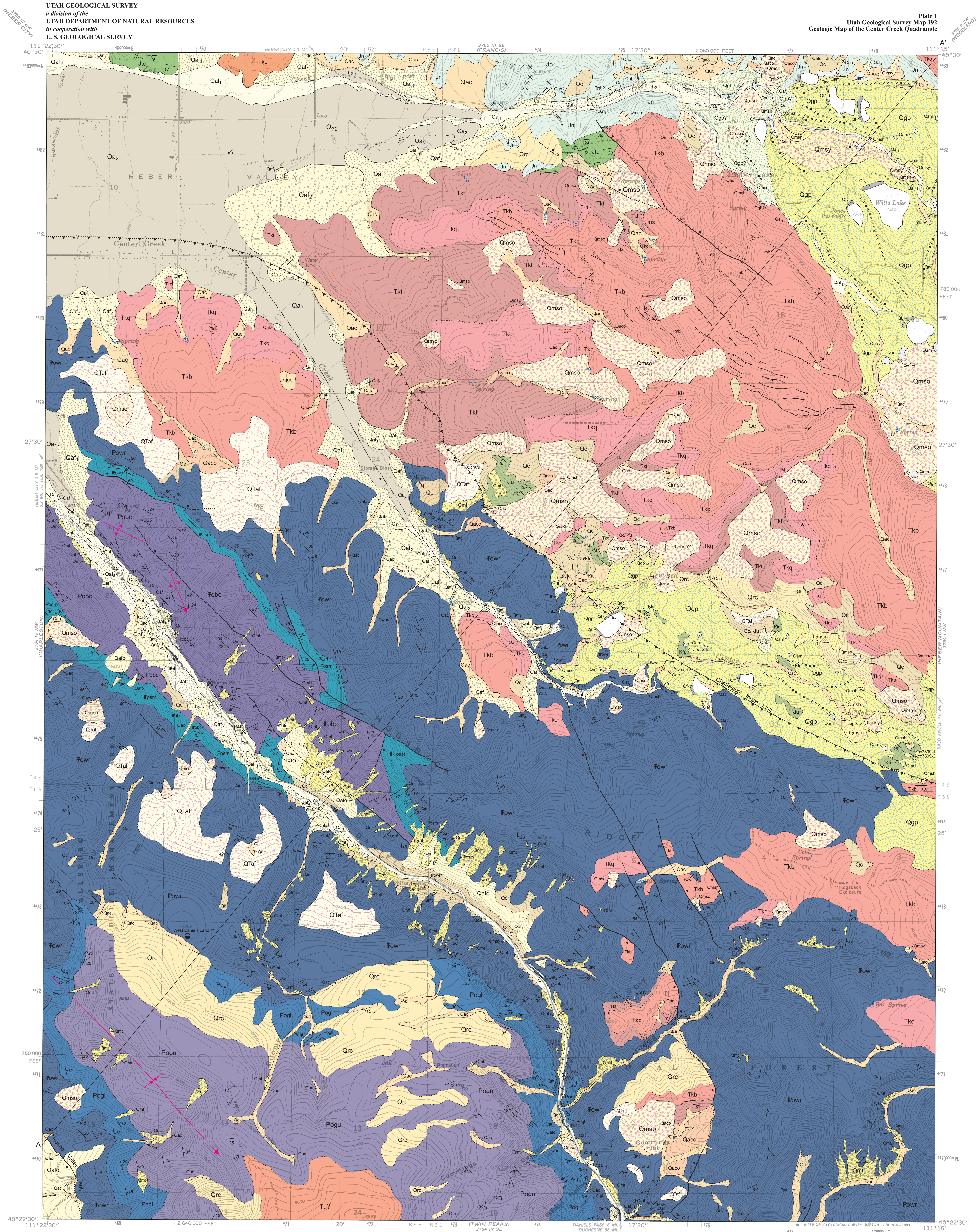


Base map from U.S. Geological Survey
Center Creek 7.5' quadrangle, 1993

SCALE 1 : 24,000

1 1/2 0 1 MILE

1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

1 .5 0 1 KILOMETER

CONTOUR INTERVAL 40 FEET

NATIONAL GEODETIC VERTICAL DATUM OF 1929

13°
231 mils

2003 MAGNETIC DECLINATION
AT CENTER OF SHEET

UTAH

QUADRANGLE LOCATION

Lori J. Douglas, Cartographer
STATEMAP Agreement 98HQAG2067

GEOLOGIC MAP OF THE CENTER CREEK QUADRANGLE, WASATCH COUNTY, UTAH

by

Robert F. Biek,
Michael D. Hylland,
John E. Welsh (deceased),
and Mike Lowe

2003

DESCRIPTION OF MAP UNITS

Qal1 Alluvial deposits (Holocene) - *Moderately to well-sorted sand, silt, clay, and pebble to boulder gravel: includes river-channel and flood-plain deposits, and terraces up to 10 feet (3 m) above current stream level; locally includes small alluvial-fan and colluvial deposits; 0 to 20 feet (0-6 m) thick.*

Qat2,3 Stream-terrace deposits (upper Pleistocene) - *Moderately to well-sorted sand, silt, clay, and pebble to boulder gravel that forms level to gently sloping surfaces above modern drainages; deposited principally in river-channel and flood-plain environments; subscript denotes relative age and height above modern drainage with level 2 deposits about 10 to 35 feet (3-11 m) and level 3 deposits 35 to 60 feet (11-18 m) above modern drainages; stream-terrace deposits are likely in part from glacial outwash; 0 to about 45 feet (0-14 m) thick.*

Qam Alluvial mud deposits (Holocene to upper Pleistocene) - *Dark-gray-brown clay and silt with organic matter; deposited in shallow depressions on the surface and along the margins of glacial moraine; 0 to 5 feet (0-2 m) thick.*

Qa2,3 Valley-fill deposits (upper Pleistocene to Holocene) - *Moderately sorted sand, silt, and pebble to boulder gravel in Heber Valley; moderately well-developed secondary calcium-carbonate in upper part of Qa2 deposit (Stage II to II+ carbonate of Birkeland and others, 1991); subscript denotes height above modern drainage and relative age, although differences are minor; probably deposited as glacial outwash in braided channels: probably less than 100 feet (30 m) thick.*

Qao Old alluvial deposits (Pleistocene) - *Moderately sorted sand and pebble to boulder gravel; contains subrounded Oquirrh Formation orthoquartzite and limestone clasts, and pebbly tuffaceous sandstone cobbles from the Keetley Volcanics; single exposure mapped in lower reaches of Daniels Canyon where it is about 300 to 400 feet (90-120 m) above modern stream level; 0 to 20 feet (0-6 m) thick.*

Qaf1 Alluvial-fan deposits (Holocene) - *Non-stratified, poorly to moderately sorted, boulder- to clay-sized sediment deposited principally by debris flows at the mouths of drainages; probably less than 40 feet (12 m) thick.*

Qaf2 Level 2 alluvial-fan deposits (upper Pleistocene) - *Non-stratified, poorly to moderately sorted, boulder- to clay-sized sediment incised by active drainages; characterized by well-developed secondary calcium-carbonate in upper part of deposit (Stage III carbonate development of Birkeland and others, 1991) along southeast margin of Heber Valley; 0 to about 50 feet (1-15 m) thick.*

Qafo Older alluvial-fan deposits (Pleistocene) - *Non-stratified, poorly to moderately sorted, boulder- to clay-sized sediment; deeply incised, locally in excess of 200 feet (60 m) above modern drainages; 0 to about 100 feet (0-30 m) thick.*

Qf Artificial fill (Historical) - *Fill used to create retaining ponds; consists principally of local borrow material; only larger fill deposits are mapped, although fill is common in "built-up" areas, many of which are shown on the topographic base map; thickness variable.*

Qc Colluvial deposits (Holocene) - *Poorly to moderately sorted, clay- to boulder-size, locally derived sediment deposited on moderate slopes by slopewash and soil creep; locally includes talus and alluvial deposits; 0 to 30 feet (0-9 m) thick.*

Qgp Glacial till (upper Pleistocene) - *Non-stratified, poorly sorted till consisting of heterogenous mixtures of clay, silt, sand, gravel, cobbles, and boulders; clasts are subangular to well rounded and primarily consist of volcanic rocks and orthoquartzite with minor sandstone and limestone; includes local glaciofluvial deposits; Pinedale age is based on moderate to sharp morainal topographic expression and weak soil development; estimated thickness 0 to 150 feet (0-45 m).*

Qgb? Glacial till (Pleistocene) - *Till of similar character as Qgp; possible Bull Lake age based on weathering of coarse-grained volcanic clasts, soil development, and relatively subdued morainal topographic expression; estimated thickness 0 to 200 feet (0-60 m).*

Qmsh Historical landslide deposits (Holocene) - *Very poorly sorted, clay- to boulder-size, locally derived sediment deposited principally by rotational and translational downslope mass movement; characterized by hummocky topography, numerous internal scarps, chaotic bedding, and historical evidence of movement; slip surfaces occur in Cretaceous strata, Keetley Volcanics, glacial deposits, and other Quaternary deposits; the slides themselves incorporate these units and overlying deposits; thickness highly variable.*

Qmsy Younger landslide deposits (Holocene to upper Pleistocene?) - *Similar character and occurrence as Qmsh, but landslide features such as scarps and slide blocks are morphologically less distinct as the result of weathering and erosion; thickness variable, but may be as much as 75 feet (23 m) thick.*

Qmso, Qmso? Older landslide deposits (upper Pleistocene) - *Similar character and occurrence as Qmsy, but landslide features such as scarps and slide blocks are morphologically subtle or indistinguishable; queried where uncertain; includes large, deep-seated bedrock landslides; thickness variable.*

Qmt Talus deposits (Holocene) - *Very poorly sorted, angular boulders and lesser fine-grained interstitial sediments; locally derived material deposited by rock fall on and at the base of steep slopes; characterized by angular boulder fields that lack vegetation; about 0 to 30 feet (0-9 m) thick.*

Qac Alluvial and colluvial deposits (Holocene) - *Poorly to moderately sorted clay- to boulder-size, locally derived sediment deposited in swales and small drainages; generally less than 20 feet (6 m) thick.*

Qaco Older alluvial and colluvial deposits (Holocene? to Pleistocene) - *Poorly to moderately sorted, clay- to boulder-size, locally derived sediment that forms incised, inactive surfaces several tens of feet above modern drainages; 0 to about 40 feet (0-12 m) thick.*

Qrc Residual and colluvial deposits (Holocene) - *Poorly exposed, poorly to moderately sorted, clay- to boulder-size, locally derived sediments; mapped principally on north-facing slopes where it supports dense vegetation and obscures bedrock contacts; 0 to about 15 feet (0-5 m) thick.*

Qc/Kfu Colluvium over undifferentiated Frontier Formation - *Colluvial veneer less than 10 feet (3 m) thick that mostly conceals underlying Frontier Formation.*

QTaf Alluvial-fan deposits (Pleistocene to Pliocene?) - *Poorly sorted, boulder- to clay-sized sediment; forms isolated remnants up to 1,500 feet (460 m) above Daniels Creek; deposits near and northwest of Boomer Canyon consist almost exclusively of subangular, locally derived Oquirrh Formation orthoquartzite clasts; deposits near Cummings Flat contain mixed orthoquartzite and volcanic clasts and may be part of the Oligocene Keetley Volcanics; 0 to about 50 feet (0-15 m) thick.*

Ta Alluvial deposits (Pliocene? to Oligocene?) - *Moderately sorted, unconsolidated, sand- to boulder-size sediment that caps the northwest end of Hogsback Ridge, about 1,300 feet (400 m) above Daniels Creek; contains mixed, subrounded Oquirrh orthoquartzite and Keetley Volcanics clasts to 10 feet (3 m) in diameter; 0 to a few feet thick.*

Tku Keetley Volcanics, undifferentiated - *Mapped north of Lake Creek in northwest corner of quadrangle; contains mixed assemblage of subrounded volcanic and orthoquartzite pebbles to boulders; may belong to the volcanic breccia of Coyote Canyon; published K-Ar ages from outside the quadrangle are 33.6 ± 1.0 to 37.5 ± 1.3 Ma (Crittenden and others, 1973; Bromfield and others, 1977; Bryant, 1990); exposed thickness about 80 feet (24 m).*

Tkb; mb Volcanic breccia of Coyote Canyon - *Volcanic conglomerate and breccia; clasts are andesite and rhyodacite by field classification but chemically range from trachyandesite and latite to silica-poor rhyodacite (Bromfield and others, 1977); volcanic conglomerate is abundant near the base and is interbedded and intertongues upward with coarse volcanic breccia; conglomerate locally contains orthoquartzite, sandstone, and limestone clasts, especially near base of unit; marker bed (mb) is a ledge-forming, gray- to red-weathering, andesitic flow breccia about 20 feet (6 m) thick; most deposits suggest a debris-flow origin, although primary pyroclastic and flow deposits are present high in the section; 0 to more than 1,400 feet (0-430+ m) thick.*

Tkq Quartzite-boulder unit - *Unconsolidated to poorly consolidated, poorly to moderately sorted, subangular to subrounded, pebble to boulder conglomerate; consists principally of Oquirrh Formation orthoquartzite and rare limestone clasts and thins to northeast away from the Charleston thrust plate; clasts commonly fractured so deposits appear more angular than they actually are; locally contains blocks of brecciated orthoquartzite up to 200 feet (60 m) in length; locally contains Mesozoic and Paleozoic (Nugget, Thaynes, Woodside, and Park City?) clasts to 10 feet (3 m) in diameter; probably deposited in alluvial-fan enviroment shed principally to northeast off upper plate of Charleston thrust; 0 to about 450 feet (0-140 m) thick.*

Tkt Tuffaceous unit - *Very light-gray to greenish-gray tuff, tuffaceous mudstone, and tuffaceous sandstone and pebbly sandstone; rarely exposed; forms slopes covered with quartzite-boulder unit colluvium; unpublished $^{40}Ar/^{39}Ar$ ages show that lowest Keetley tuffs in the Strawberry Reservoir area and at Current Creek Peak are 37.25±0.14 Ma and 37.73±0.28 Ma; 0 to at least 720 feet (0-220+ m) thick.*

Tu? Uinta(?) Formation - *Very poorly exposed, subrounded to rounded, pebble- to boulder-conglomerate; clasts are principally Oquirrh Formation orthoquartzite and sandstone; forms residual boulder field; only the lower 350 feet (110 m) exposed.*

Kfu Frontier Formation, undifferentiated - *Interbedded mudstone, siltstone, sandstone, pebbly sandstone, and uncommon limestone; sandstone is medium to very thick bedded, very pale-orange to light-brown, calcareous, very fine- to medium-grained quartz sand; pebbly sandstone is coarser with well-rounded quartzite, chert, and limestone clasts to small cobble size; mudstone and siltstone are commonly mottled dark reddish brown and light olive gray and are slightly swelling; includes at least two limestone beds, one that is probably less than one-foot-thick (0.3 m) light-gray limestone with algal(?) structures and veins of chalcedony, and the other, which is a ledge-forming, 6-foot-thick (2 m) oyster coquina; grayish-orange to moderate-yellowish-brown, fine-grained silty sandstone and brownish-black shale under oyster bed contain abundant gastropods and bivalves indicative of an early Turonian age, uncommon fish scales, and a middle to late Cenomanian to Turonian palynomorph and dinoflagellate assemblage; incomplete section about 2,500 feet (760 m) thick.*

Kma Aspen Shale - *subsurface only*

KJdcm Dakota Sandstone and Cedar Mountain and Morrison Formations - *subsurface only*

Jsp Stump Formation and Pruess Sandstone - *subsurface only*

Ja Arapien Shale - *subsurface only*

Jtc Twin Creek LImestone - *Five undifferentiated members, from youngest to oldest, are exposed: Watton Canyon Member (55 feet [17 m] exposed thickness) is yellowish gray to medium-gray, oolitic limestone and dense, very fine-grained limestone, commonly with a conchoidal or rectilinear fracture; Boundary Ridge Member (145 feet [44 m] thick) is interbedded, red-brown siltstone and fine-grained sandstone and gray to brown sandy oolitic limestone and algal laminated limestone that forms reddish slopes; Rich Member (116 feet [35 m] thick) is medium-gray, thin- to medium-bedded, finely crystalline, ledge- and slope-forming limestone that weathers to pencil-like fragments and small chips, and very light-gray, very fine-grained calcareous sandstone with ripple marks; Sliderock Member (209 feet [64 m] thick) is brownish-gray, light-gray-weathering, slope-forming, thin- to medium-bedded, dense limestone with a conchoidal fracture, light-gray micritic limestone that weathers to pencil-like fragments, and medium-gray, dense, finely crystalline to very fine-grained limestone with* Isocrinus *sp. (formerly Pentacrinus) and fossil hash near the top; Gypsum Spring Member (83 feet [25 m] thick) is slope- and ledge-forming, dark-reddish-brown to gray, dense, very fine-grained limestone with a conchoidal fracture; maximum exposed thickness 608 feet (185 m). Measured by Doug Sprinkel and Hellmut Doelling (UGS unpublished data, June 22, 1999).*

Jn Nugget Sandstone - *Moderate-reddish-orange to moderate-orange-pink, massively cross-bedded, moderately well-cemented, generally noncalcareous, well-rounded, fine- to medium-grained, frosted quartz sandstone; upper part is generally white to very pale orange; variably jointed; deposited in a vast coastal and inland dune field; only upper part exposed; about 1,260 feet (385 m) thick in West Daniels Land #1 well.*

Ŧa Ankareh Formation - *subsurface only*

Ŧt Thaynes Formation - *subsurface only*

Ŧw Woodside Shale - *subsurface only*

Ppc Park City and Phosphoria Formations - *subsurface only*

Pw Weber Sandstone - *subsurface only*

Pogu Granger Mountain Member, upper unit - *Interbedded, medium- to thick-bedded, commonly bioturbated, fine- to medium-grained, commonly calcareous, feldspathic sandstone, and dark-gray, laminated to thin-bedded, pyritic siltstone; poorly exposed; sandstones form more rounded exposures than Pennsylvanian strata; only the lower 2,000 feet (600 m) exposed in the quadrangle, but the unit is 10,250 feet (3,125 m) thick at Wallsburg Ridge, about 5 miles (8 km) west of the quadrangle.*

Pogl Granger Mountain Member, lower unit - *Medium- to very thick-bedded, medium-gray, ledge-forming, fossiliferous limestone with few thin beds and nodules of black chert separated by middle, slope-forming, yellowish-brown, calcareous siltstone with few thin limestone interbeds; abundant* Schwagerina*-type fusilinids, locally common rugose and* Syringoporid*-type corals, bryozoans, and crinoid stems; 300 to 500 feet (90-150 m) thick.*

Ꝑowr Wallsburg Ridge Member - *Thick- to very thick-bedded, yellowish-brown, siliceous, feldspathic sandstone (orthoquartzite); common conchoidal fracture; locally laminated to cross-bedded; bedding commonly difficult to determine; includes few thin, silty and sandy limestone interbeds; about 3,700 feet (1,130 m) thick.*

Ꝑosm Shingle Mill Limestone Member - *Consists of two principal limestone intervals separated by a thick unit of thin- to very thick-bedded, yellowish-brown to light-olive-gray, very fine- to medium-grained, commonly calcareous, slightly feldspathic quartz sandstone with low-angle cross-bedding; limestone is thin to very thick bedded, gray, with black chert stringers and nodules; uncommon crinoid stems, solitary corals, and brachiopods; lower limestone commonly poorly exposed; about 380 to 510 feet (115-155 m) thick.*

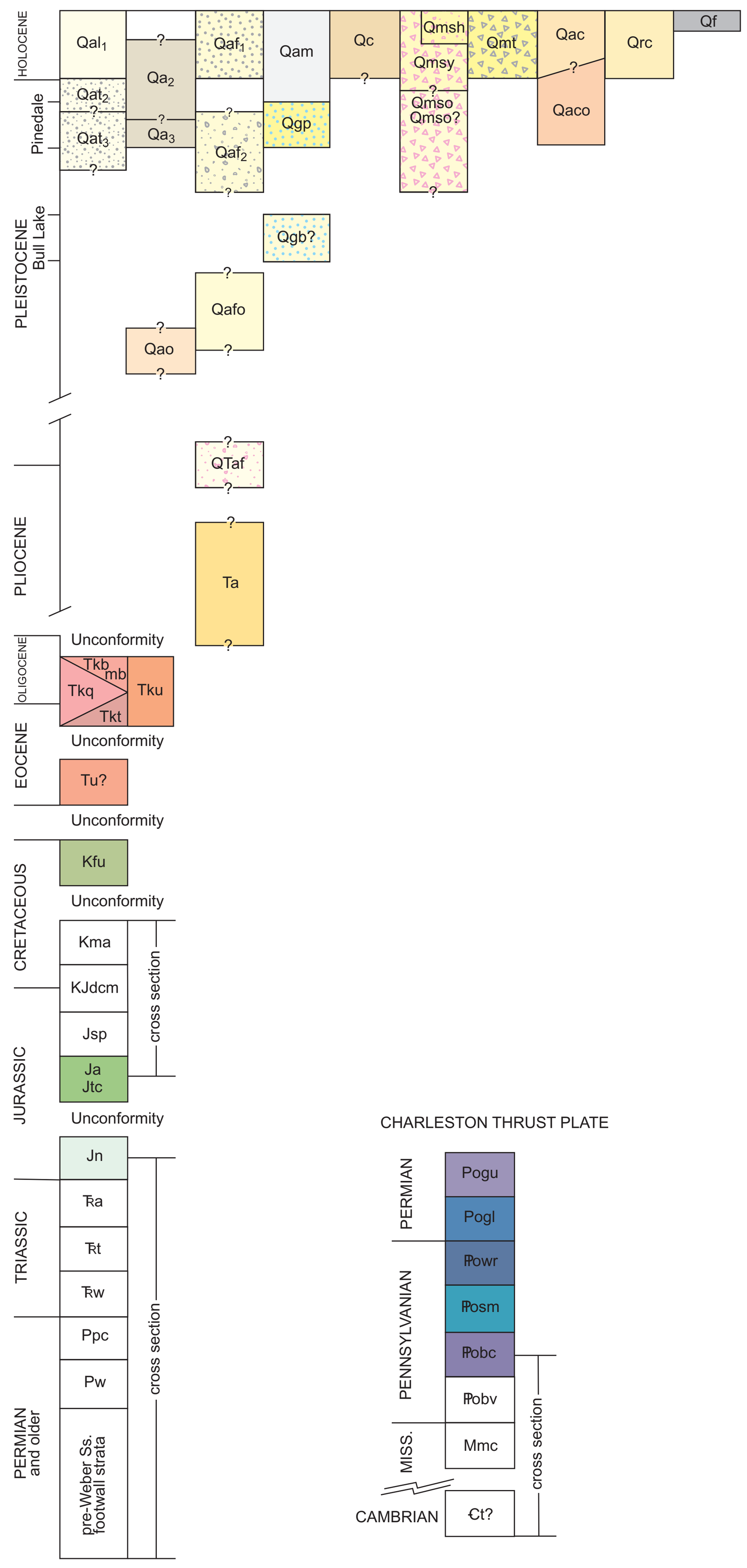
Ꝑobc Bear Canyon Member - *Sandstone with lesser interbedded limestone; sandstone is yellowish brown, very fine grained, feldspathic, siliceous or calcareous, and commonly finely laminated; limestone is medium to thick bedded, medium gray with local black chert nodules and stringers, commonly has coarser grained, brown-weathering, planar cross-laminae that stand in relief, and local crinoid stems, bryozoans, and brachiopods; only about the upper 2,000 feet (600 m) exposed, but the formation is about 4,600 feet (1,400 m) thick in the West Daniels Land #1 well.*

Ꝑobv Bridal Veil Falls Limestone Member - *subsurface only*

Mmc Manning Canyon Shale - *subsurface only*

Ꞓt? Tintic Quartzite? - *subsurface only*

CORRELATION OF MAP UNITS



LITHOLOGIC COLUMN

SYSTEM	SERIES & STAGE			FORMATION/UNIT		MAP SYMBOL		THICKNESS feet (meters)	LITHOLOGY
QUATERNARY	Holocene Pleistocene			Surficial deposits		Q, QT, Ta		Variable	
TERTIARY	Neogene	Pliocene							
		Oligocene		Keetley Volcanics	Volcanic breccia of Coyote Canyon	Tku	Tkb	0-1,400+ (0-430+)	top not exposed; marker bed (mb)
					Quartzite-boulder unit		Tkq	0-450 (0-140)	
					Tuffaceous unit		Tkt	0-720+ (0-220+)	mostly covered; base not exposed
	Eocene			Uinta ? Fm.		Tu?		350+ (110+)	top not exposed
CRETACEOUS	Upper	Turonian		Mancos Group	Frontier Fm.	Kfu		2,500+ (760+) incomplete section	oyster bed; base not exposed
		Cenomanian (?)							
					Aspen Shale	Kma		not exposed; shown on cross section only	
	Lower			Dakota Ss. Cedar Mtn. Fm. Morrison Fm.		KJdcm			
JURASSIC	Upper								
	Middle			Stump Fm. Pruess Ss.		Jsp			
		Callovian		Arapien Shale		Ja			
		Bathonian		Twin Creek Ls.		Jtc		608 (185)	top not exposed; J-2 unconformity
	Lower			Nugget Ss.		Jn		1,260 (385)	base not exposed
TRIASSIC	Upper			Ankareh Fm.		Ŧa		not exposed; shown on cross section only	
	Lower			Thaynes Fm.		Ŧt			
				Woodside Shale		Ŧw			
PERMIAN	Lower			Park City and Phosphoria Formations		Ppc			
PENNSYLVANIAN AND OLDER				Weber Sandstone		Pw			
				pre-Weber footwall strata					

CHARLESTON THRUST PLATE

SYSTEM	SERIES	STAGE	FORMATION	MEMBER	UNIT	MAP SYMBOL	THICKNESS feet (meters)	LITHOLOGY
PERMIAN	Lower	Wolfcampian	Oquirrh Formation	Granger Mtn. Mbr.	upper unit	Pogu	lower 2,000 (600) exposed 10,250 (3,125) total	top not exposed; black shale
					lower unit	Pogl	300 to 500 (90-150)	fossiliferous limestone
PENNSYLVANIAN	Upper	Virgilian ? Missourian		Wallsburg Ridge Member		Ꝑowr	3,700 to 3,900 (1,130-1,190)	
				Shingle Mill Limestone Mbr.		Ꝑosm	380 to 510 (115-155)	cherty limestone
	Middle	Desmoinesian Atokan		Bear Canyon Member		Ꝑobc	2,000 (600) exposed 4,600 (1,400) total	base not exposed
	Lower	Morrowan		Bridal Veil Falls Ls. Member		Ꝑobv	not exposed; shown on cross section only	
MISSISSIPPIAN	Upper		Manning Canyon Shale			Mmc		
fault								
CAMBRIAN	Lower to Middle		Tintic Quartzite?			Ꞓt?		
Charleston thrust fault								

MAP SYMBOLS

- Contact - *dashed where approximately located*
- Mass-movement scarp - *hachures on down-dropped side*
- Axis of double-crested ridge associated with possible sackungen
- mb Marker bed in Keetley Volcanics
- Moraine crest
- ?. Normal fault - *dashed where approximately located, dotted where concealed, queried where uncertain; bar and ball on down-thrown side; no bar and ball indicates fault with unknown offset*
- ? Thrust fault - *dotted where concealed, queried where uncertain; teeth on upper plate*
- Axial trace of anticline - *showing direction of plunge*
- Axial trace of syncline - *showing direction of plunge*
- 30 Strike and dip of inclined bedding
- 15 Strike and dip of inclined bedding determined using stereoplotter
- Approximate strike and dip direction of inclined bedding
- Spring
- Quarry - *sandstone (no letter), quartzite (q)*
- Pit - sand and gravel or borrow material
- Oil exploration test hole - *plugged and abandoned*
- cc7899-1 Sample location and number
- B-14 Borehole
- Measured section location

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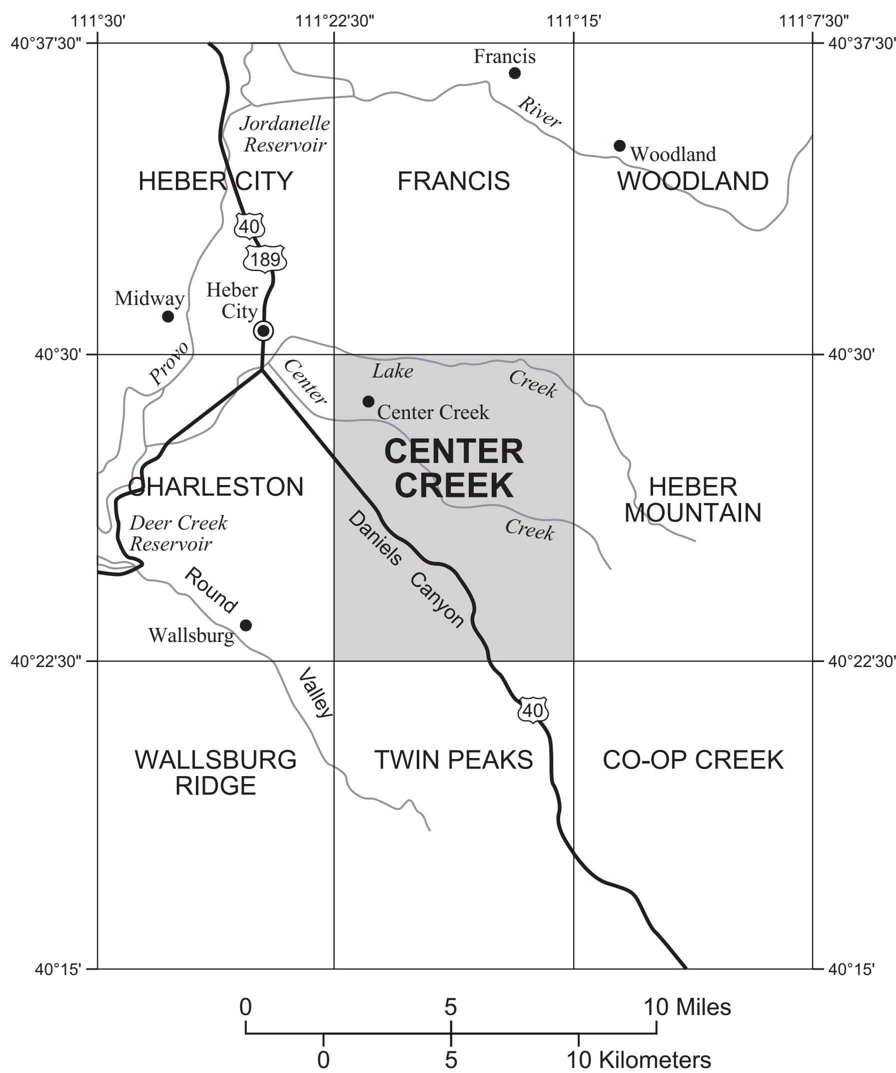

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3//03

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Robert F. Biek, Michael D. Hylland, John E. Welsh (deceased), and Mike Lowe

ABSTRACT

The Center Creek quadrangle lies astride a structural and topographic saddle between the Wasatch Range and Uinta Mountains. The quadrangle includes three distinct groups of rocks: (1) allochthonous, Permian to Pennsylvanian Oquirrh Formation in the Charleston thrust plate that is deformed into two large, southeast-plunging folds; (2) parautochthonous, southwest-dipping Mesozoic strata beneath the Charleston thrust; and (3) subhorizontal, Oligocene to Eocene clastic and volcanic rocks that unconformably overlie older strata.

Allochthonous strata are bounded on the northeast by the Charleston thrust, which trends southeast up the Center Creek drainage under a cover of Quaternary deposits. The thrust ramps stratigraphically upsection to the northeast, and at the surface places the Upper Pennsylvanian Wallsburg Ridge Member of the Oquirrh Formation against strata herein assigned to the undifferentiated lower Frontier Formation of early Late Cretaceous (early Turonian) age. The distribution of the Oligocene to Eocene Keetley Volcanics – which here consist of a lower tuffaceous unit, a middle quartzite-boulder unit that thins to the northeast, and the upper volcanic breccia of Coyote Canyon – help to identify a post-Keetley extensional fault that extends from the mouth of the Center Creek drainage south-southeast to the southern boundary of the quadrangle. The down-to-the-west displacement on this normal fault is about 800 feet (250 m).

Deposits and landforms associated with the Pinedale and possibly Bull Lake glaciations are present in the Lake Creek drainage, and Pinedale glacial deposits are newly recognized in the Center Creek drainage. Hummocky ground moraine, lateral and end moraines, and broad cirques in the adjacent Heber Mountain quadrangle characterize these drainages. Glacial outwash deposits are widespread in the eastern portion of Heber Valley, and may be present upstream in the lower reaches of both the Center Creek and Lake Creek drainages.

The principal economic resources of the quadrangle are aggregate, particularly crushed quartzite from the Wallsburg Ridge Member of the Oquirrh Formation, and rough building stone quarried from the Nugget Sandstone. Numerous springs and streams in the quadrangle, and ground water from the eastern end of Heber Valley, provide water for domestic use and irrigation.

Geologic hazards in the Center Creek quadrangle include landslides, flooding, debris flows, shallow ground water, problem soil and rock, earthquakes, and radon. We mapped numerous landslides in the quadrangle, many of which show evidence of historical movement. Some of these landslides were previously unmapped, including ridge-top deformation features that may be sackungen, which are thought to result from large-scale, deep-seated gravitational spreading. Landslides typically occur in Pleistocene glacial deposits, the Keetley Volcanics, and the Frontier Formation, as well as colluvial and residual deposits derived from these units.

INTRODUCTION

The Center Creek quadrangle lies about 35 miles (55 km) southeast of Salt Lake City in a structural and topographic saddle between the Wasatch Range and Uinta Mountains. The quadrangle includes the eastern part of Heber Valley and adjacent foothills, which are experiencing significant population and recreational growth (figure 1). Geologic hazards associated with landslides, earthquakes, flooding, problem soils, and other factors are known in the quadrangle and surrounding area. This geologic map and report provide basic geologic information necessary to further evaluate the geologic hazards and resources in the area.

The Center Creek quadrangle lies in what Stokes (1986) referred to as the Wasatch Hinterlands portion of the Middle Rocky Mountains physiographic province. The quadrangle includes the lower parts of three principal drainages: Daniels Canyon, which is traversed by U.S. Highway 40; Center Creek, which occupies a structural divide between allochthonous and parautochthonous strata; and Lake Creek, which is the site of significant residential development. Elevations in the quadrangle range from about 5,800 feet (1,770 m) in the northwest to 9,200 feet (2,800 m) in the southeast parts of the quadrangle. Much of the southern half of the quadrangle is public land managed by the U.S. Forest Service, whereas most land in the northern half of the quadrangle is privately owned.

The Uinta Mountains and Wasatch Range have been the focus of numerous geologic investigations. In contrast, the geology of the Center Creek area has not been widely stud-

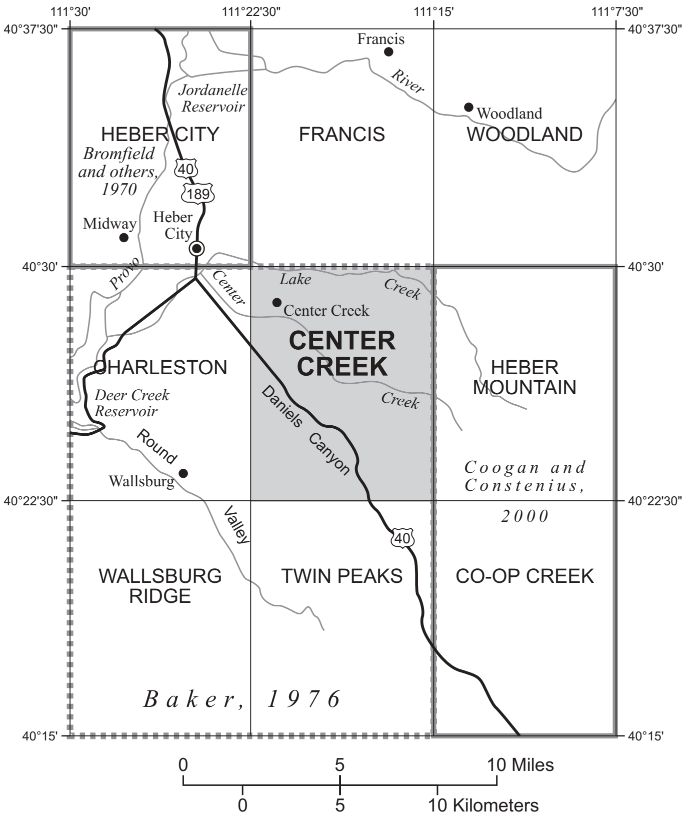

Figure 1. Index map showing the Center Creek 7.5-minute quadrangle and surrounding area. Geologic maps of adjacent quadrangles are also shown; Bryant's (1992) 1:125,000-scale geologic map of the Salt Lake City 1° x 2° quadrangle covers all of these quadrangles.

ied, principally due to generally poor and limited bedrock exposures. Baker (1959) produced a 1:215,000-scale geologic map of the greater Wasatch Range near Provo, including the Center Creek quadrangle. He later mapped the Center Creek quadrangle at a scale of 1:63,360 as part of the west half of the Strawberry Valley quadrangle (Baker, 1976). In his unpublished 1980-81 study of the stratigraphy and structure of Permian and Pennsylvanian strata of part of the Charleston allochthon, co-author John Welsh mapped most of the Center Creek and adjacent Charleston, Co-op Creek, and Twin Peaks quadrangles at a scale of 1:24,000. In his 1:500,000-scale geologic map of Utah, Hintze (1980) shows an erosional window in the Charleston thrust at Center Creek exposing a structurally complex sequence of Late Paleozoic to Eocene strata, but we interpret the geology differently. Bryant (1992) completed a 1:125,000-scale geologic map of the Salt Lake City 1° x 2° quadrangle and was the first to identify Cretaceous strata in the Center Creek quadrangle. Geologic maps of adjacent areas include those of Bissell (1952), who mapped the northeast Strawberry Valley quadrangle at a scale of 1:87,000; McDougald (1953), who mapped the Francis area at a scale of 1:31,680; Bromfield and others (1970), who mapped the Heber (City) quadrangle at 1:24,000; Astin (1976), who mapped the Co-op Creek quadrangle at a scale of 1:48,000; and Coogan and Constenius (2000), who mapped the Heber Mountain and Co-op Creek quadrangles at a scale of 1:50,000 as part of a larger map of the east part of the Provo 30 x 60-minute quadrangle. Bryant (1990) produced a 1:100,000-scale map of the Salt Lake City 30 x 60-minute quadrangle. Hylland and others (1995) produced an engineering geologic map folio of western Wasatch County, which includes most of the Center Creek quadrangle.

STRATIGRAPHY

The Center Creek quadrangle includes three distinct groups of rocks: allochthonous Permian to Pennsylvanian rocks of the Charleston thrust plate that are deformed into two large, southeast-plunging folds; parautochthonous, southwest-dipping Mesozoic strata below the Charleston thrust; and Eocene to Oligocene clastic and volcanic rocks that unconformably overlie older strata and mostly conceal the Charleston thrust. A variety of Quaternary deposits, including high-level alluvial deposits in Daniels Canyon and glacial deposits in both the Lake and Center Creek drainages, record the evolution of the present landscape.

Unlike areas to the south and east near the Strawberry and Nebo thrusts, there are no coarse, middle to late Cretaceous synorogenic strata exposed in front of the Charleston thrust. Such sediments certainly were deposited in front of the Charleston thrust as they were to the south along the Strawberry-Nebo thrust, but they were likely eroded as a result of subsequent uplift of the Uinta Mountains. Some synorogenic deposits could be preserved beneath a cover of Keetley Volcanics in the structural saddle between the Uinta Mountains and Wasatch Range.

Permian and Pennsylvanian

Oquirrh Formation

Oquirrh strata consist of up to 25,000 feet (7,600 m) of Lower Permian to Pennsylvanian sandstone, orthoquartzite, shale, and limestone deposited in the Oquirrh marine basin of north-central Utah and southern Idaho (Welsh and Bissell, 1979). The Oquirrh is elevated to group status in the Oquirrh Mountains and Tintic district to the west, but in the Wasatch Range it was conferred the rank of formation by Baker (1976). In the Wasatch Range, the Oquirrh Formation is divided into five members; in ascending order these are the Bridal Veil Falls, Bear Canyon, Shingle Mill Limestone, Wallsburg Ridge, and Granger Mountain Members. Only the upper part of the Bear Canyon Member through the basal Granger Mountain Member is exposed in the Center Creek quadrangle. Regional correlations of member and formational names were summarized by Baker (1976) and Welsh and Bissell (1979).

Bear Canyon Member (ℙobc): Only about the upper 2,000 feet (600 m) of the Bear Canyon Member is exposed in the Center Creek quadrangle where it forms steep, ledgy slopes mostly covered by colluvium in the core of the Daniels Canyon anticline. The upper Bear Canyon Member consists mostly of sandstone with lesser interbedded limestone. The sandstone is yellowish brown, very fine grained, finely laminated, feldspathic, and is well indurated with a siliceous, or less commonly, calcareous cement. Most sandstone beds are resistant and commonly display a prominent conchoidal fracture. The sandstones commonly have a light-yellow goethetic stain from a trace of pyrite.

The limestone beds of the upper Bear Canyon Member are exposed immediately north of State Highway 40 in the NE¼ section 27 and in the SW¼SE¼ section 36, T. 4 S., R. 5 E. These limestones are principally medium to thick bedded, medium gray, coarse grained, and fossiliferous, with local black chert nodules and stringers. Limestones exposed near State Highway 40 lie on the south flank of the Daniels Canyon anticline and total several tens of feet thick. The limestones become thicker bedded and sandy with planar cross-laminae and less chert down section to the north. The cross-laminae weather brown and gray, with the brown, coarser grained laminae standing in relief. Crinoid stem, fenestrae bryozoan, and small brachiopod fossils are common in these beds. These limestone beds are not exposed on the north flank of the anticline due to truncation by a northwest-trending, down-to-the-north normal fault. Based on map patterns and assuming minimal structural complications that may be concealed by surficial deposits of Daniels Canyon, these limestone beds are probably about 1,500 to 1,800 feet (460-550 m) below the top of the Bear Canyon Member.

Two limestone beds, each about 10 feet (3 m) thick, are exposed in section 36, on the nose of the Daniels Canyon anticline. These limestone beds are separated by a covered interval about 20 feet (6 m) thick that probably consists of light-olive-gray, very fine- to fine-grained calcareous sandstone similar to that exposed below the lower limestone. The enclosing carbonate units are thin- to very thick-bedded, generally fine- to medium-grained limestone with about 10 percent black chert stringers. These limestones contain rugose corals and partially articulated crinoid stems. Limestones of the upper bed tend to be coarser grained. These two limestone beds lie about 250 feet (75 m) below the top of the Bear Canyon Member.

In contrast, in an unpublished measured section of the Bear Canyon Member at the west end of Wallsburg Ridge (just 10 miles [16 km] to the west) that totaled about 9,200 feet (2,800 m) thick, Welsh found the stratigraphically highest limestone beds to be about 2,340 feet (715 m) below the top of the section. He similarly noted limestones about 1,300 feet (400 m) and 1,800 feet (550 m) below the top of the Bear Canyon Member in the West Daniels Land #1 well (south of Daniels Canyon in section 11, T. 5 S., R. 5 E.), in which the Bear Canyon Member is probably about 4,600 feet (1,400 m) thick. Thus, the limestone beds exposed in the Center Creek quadrangle are apparently absent at Wallsburg Ridge and possibly in the West Daniels Land #1 well, illustrating east-west facies changes that typify sedimentation along the eastern margin of the Oquirrh basin. These sections, and others in the region, point to the highly variable amount of limestone in the Bear Canyon Member, with some areas apparently receiving greater clastic input from the nearby Uncompahgre uplift. The variable thicknesses also reflect the presence of a regional disconformity that separates Middle Pennsylvanian (Desmoinesian) and Upper Pennsylvanian (Missourian) rocks (Welsh and Bissell, 1979).

Fusulinid zones of *Fusulinella*, *Wedekindellina*, and *Fusulina* place the Bear Canyon Member in the Atokan and Desmoinesian stages (Middle Pennsylvanian). The lithologies and fauna indicate that the Bear Canyon Member was deposited in a moderately deep shelf or shallow-marine basin. Limestone muds, common in the lower and middle parts of the member, were deposited in quiet water with a sparse fauna of benthonic bryozoa, few fusulinids, and chonetid and productid brachiopods. Periodically the lime muds were overwhelmed by influxes of arkosic sand from the Uncompahgre uplift and to a lesser extent by coarse carbonate debris and rounded quartz grains from sources outside or marginal to the basin. The carbonate debris probably washed in from the shallow Callville platform that covered the Emery High to the south and southeast (Welsh and Bissell, 1979).

Shingle Mill Limestone Member (IPosm): The Shingle Mill Limestone Member forms an important marker in a thick mass of similar sandstones of the Bear Canyon and Wallsburg Ridge Members. The Shingle Mill Limestone Member forms ledgy outcrops in the lower reaches of Daniels Canyon where it helps define the Daniels Canyon anticline. The member consists of two thick limestone intervals separated by about 200 feet (60 m) of sandstone. One or both of these limestones are commonly poorly exposed due to cover by talus and colluvium, as discussed below. The best exposures of these limestone intervals are at the southeast-plunging nose of the anticline along a southwest-trending spur at the common border of section 1, T. 5 S., R. 5 E. and section 36, T. 4 S., R. 5 E. (figure 2). Good exposures are also in the NW¼ section 36, T. 4 S., R. 5 E., and on southwest-trending spurs near the center of section 26, T. 4 S., R. 5 E.

Along the nose of the Daniels Canyon anticline, the

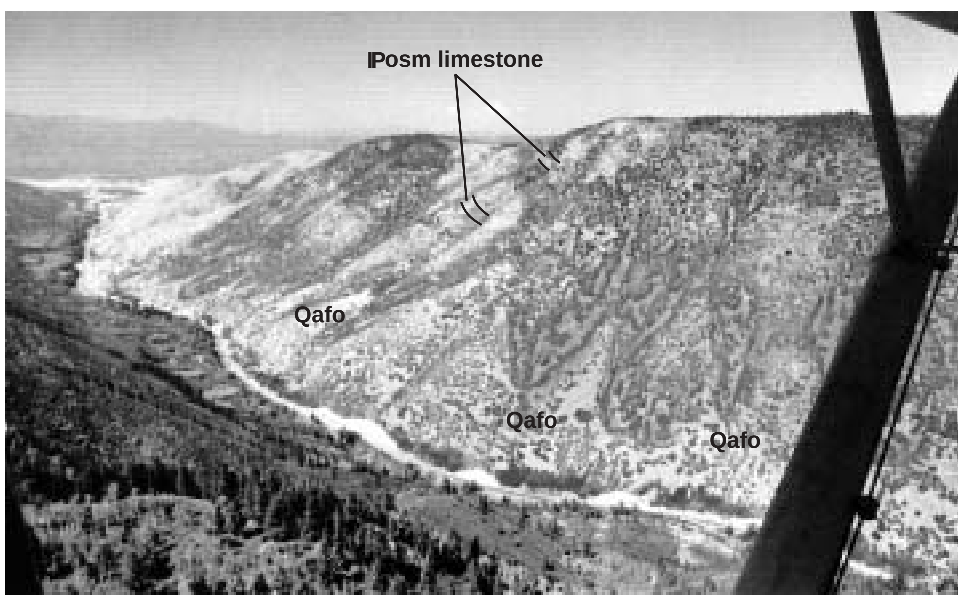

Figure 2. *Oblique aerial view of the south-facing slope of Hogsback Ridge in the lower reaches of Daniels Canyon. Note ledges of the Shingle Mill Limestone Member (IPosm) exposed on the southeast-plunging nose of the Daniels Canyon anticline. Older alluvial-fan deposits (Qafo), and talus characterized by stone stripes, cover a mid-level bench and adjacent slopes carved into Oquirrh strata. Photograph taken by Welsh in 1981.*

lower limestone interval is about 80 feet (24 m) thick. It consists of thin- to very thick-bedded, medium-gray, variably silty limestone with common black chert nodules and stringers. It becomes coarser grained, more fossiliferous, and cliff-forming upward, where it grades into a yellowish-brown- and rounded-weathering, thin- to very thick-bedded, very fine- to medium-grained, calcareous, slightly feldspathic quartz sandstone with low-angle cross-stratification. This sandstone interval is about 200 feet (60 m) thick and is overlain by an upper, cliff-forming limestone interval that is about 100 feet (30 m) thick. This upper limestone is fine grained, medium gray, with abundant black chert nodules and thin beds that make up 25 percent or more of the unit and impart a thin-bedded appearance to the cliffs. Fossils are uncommon in these beds in the Center Creek quadrangle, but Welsh (unpublished notes, 1980-81) noted that the upper limestone interval at Wallsburg Ridge contains a benthic fauna of *Chonetes*, *Marginifera*, *Dictyoclostus*, rhynchonellids, bryozoa, crinoids, and trochoid gastropods.

These two limestone intervals are also exposed in the NW$^1/_4$ section 36, NW$^1/_4$NE$^1/_4$ section 34, and SE$^1/_4$SW$^1/_4$ section 27, T. 4 S., R. 5 E. However, map patterns show the Shingle Mill Limestone Member thins considerably in sections 22 and 26, along the north flank of the anticline near the crest of Hogsback Ridge. Here, possibly, only the lower limestone interval is included in the map unit. Exposures on the north side of Hogsback Ridge are extremely poor, and we found no limestone outcrop or float north of the ridge crest.

Baker (1976) included only the upper limestone interval in the Shingle Mill Limestone in the Daniels Canyon and Wallsburg Ridge area. We include both limestone intervals in the Shingle Mill Limestone Member based on Welsh's (unpublished notes, 1980-81) correlation that shows the lower and upper limestone intervals are equivalent to the Jordan and Commercial Limestones, respectively, of the Oquirrh Mountains. The *Eowaringella* fusulinid zone is in the basal part of the lower limestone, the same position in which it is found at Middle Canyon in the Oquirrh Mountains and at South Mountain. In the Center Creek quadrangle, *Eowaringella* was collected from beds near the center of section 26, T. 4 S., R. 5 E. No fusulinids have been found in the upper limestone interval or in the Commercial Limestone. However, 225 feet (69 m) above this limestone interval at Wallsburg Ridge, Welsh (unpublished notes, 1980-81) recovered the Missourian fusulinid *Triticities* from lower Wallsburg Ridge Member strata. Baker (1976) collected fusulinids from Shingle Mill strata on the west side of Wallsburg Ridge, in section 5, T. 6 S., R. 4 E., that were initially misidentified as Desmoinesian in age, but that were later reclassified as earliest Missourian (Raymond C. Douglass, U.S. Geological Survey, written communication, January 28, 1981).

In an unpublished measured section at Wallsburg Ridge, about 8 miles (13 km) west of Daniels Canyon, Welsh measured about 1,145 feet (350 m) of Shingle Mill strata. He found the lower limestone is about 230 feet (70 m) thick, the middle sandstone unit about 500 feet (150 m) thick, and the upper limestone interval about 385 feet (117 m) thick. In the West Daniels Land #1 well, Welsh (unpublished notes, 1980-81) assigned about 110 feet (34 m) to the lower limestone, 140 feet (43 m) to the middle sandstone, and 260 feet (79 m) to the upper limestone. These measurements, and those cited above for exposures in Daniels Canyon, illustrate an eastward thinning of these early Late Pennsylvanian strata.

Wallsburg Ridge Member ($\mathbb{P}$owr): The Wallsburg Ridge Member was named by Baker (1976) for a thick sequence of siliceous, slightly feldspathic sandstones exposed along the crest of Wallsburg Ridge, just west of the Center Creek quadrangle. In the Center Creek quadrangle, the Wallsburg Ridge Member forms steep, commonly densely vegetated, colluvium-covered slopes over much of the southern half of the quadrangle. Exposures, however, are few, and marker beds nonexistent, so that mapping of Wallsburg Ridge strata is mostly limited to measuring bedding attitudes.

The Wallsburg Ridge Member consists of a monotonous mass of yellowish-brown, fine- to medium-grained, well-indurated, siliceous sandstones (orthoquartzite) that typically contain 2 to 5 percent feldspar. The sandstones are commonly finely laminated and cross-laminated in thick to very thick beds, and are barren except for uncommon trace fossils on some bedding planes. These sandstones are highly fractured nearly everywhere, and brecciated near faults, so that bedding is difficult to determine and attitudes surprisingly difficult to obtain. Low-angle cross-laminae commonly form large wedge-shaped sets up to tens of feet in length. Combined with poor exposures, measurements on such beds can easily give erroneous strikes and dips. The sandstones commonly have a conchoidal fracture.

Interbedded with these feldspathic sandstones are a few thin silty and sandy limestones. Welsh noted five such beds in his unpublished measured section of Wallsburg Ridge, and over 30 such beds in correlative strata in the Oquirrh Mountains. These calcareous beds contain a benthic fauna of *Caninia* (rugosa) and syringoporid corals, fusulinids, and disarticulated crinoid columns.

In the upper reaches of Center Canyon, in the NW$^1/_4$SE$^1/_4$NW$^1/_4$ section 15, T. 5 S., R. 6 E., Wallsburg Ridge strata contain a ledge-forming, clast-supported boulder conglomerate of possible turbidite origin. The clasts are subangular to subrounded, both siliceous and calcareous sandstone up to 3 feet (1 m) in diameter set in a sandy calcareous matrix. Several thin limestone beds and an intraformational limestone conglomerate are exposed on the south-facing hillside in the SE$^1/_4$SE$^1/_4$SW$^1/_4$ section 34, T. 4 S., R. 6 E.

In his unpublished measured section at Wallsburg Ridge, about 8 miles (13 km) west of Daniels Canyon, Welsh measured about 5,200 feet (1,580 m) of Wallsburg Ridge strata, but noted that due to difficulty in obtaining accurate strike and dip measurements, the section thickness may be off by 10 percent. The West Daniels Land #1 well penetrated a nearly complete section of 4,150 feet (1,265 m) of the Wallsburg Ridge Member; however, strata there dip about 25 degrees southwest so that the stratigraphic thickness of the member is about 3,700 to 3,900 feet (1,130-1,190 m). Correlative strata in the Oquirrh Mountains are approximately 6,500 feet (2,000 m) thick, again illustrating the thinning of strata towards the eastern margin of the Oquirrh basin. Baker (1976) collected Missourian to Virgilian (Late Pennsylvanian) fusulinids from Wallsburg strata at Wallsburg Ridge.

Granger Mountain Member: The lower part of the Granger Mountain Member is exposed southwest of State Highway 40 where it can be divided into two informal map units: a lower unit of limestone and siltstone and an upper, much thicker unit of interbedded sandstone and siltstone. To the west at Wallsburg Ridge, Welsh (unpublished notes, 1980-81) measured about 10,250 feet (3,125 m) of Granger Mountain strata, but only about the lower 2,500 feet (760 m) is present in the Center Creek quadrangle. Baker (1976) assigned just 7,300 feet (2,230 m) to the Granger Mountain Member at Wallsburg Ridge.

Lower unit (Pogl): The lower unit consists of two ledge- and cliff-forming limestone intervals of about equal thickness separated by a middle, somewhat thicker, slope-forming siltstone interval. Collectively, these limestones form an important marker in a vast thickness of Oquirrh sandstone and siltstone. The limestones are best exposed at the mouth of Parker Canyon and along the nose and west flank of the Big Hollow syncline. The limestones are medium to very thick bedded, medium gray, fossiliferous, and contain a few thin, discontinuous beds and nodules of black chert. The limestones contain abundant *Schwagerina*-type fusulinids characteristic of the Early Permian (Wolfcampian), common bryozoans and rugose and syringoporid corals, and uncommon crinoid stems and brachiopods. The middle siltstone interval consists of yellowish-brown calcareous siltstone with few thin limestone interbeds.

Map patterns indicate that the lower Wolfcampian limestone unit thins to the west, from about 500 feet (150 m) thick at Parker Canyon on the east limb of the Big Hollow syncline to about 300 feet (90 m) thick on the west limb. These limestones are not present at Wallsburg Ridge about 5 miles (8 km) to the southwest.

Upper unit (Pogu): The upper unit consists of the Freeman Mountain sandstone facies and Curry Peak siltstone facies and forms densely vegetated slopes with remarkably few exposures. At Wallsburg Ridge, west of the quadrangle, Welsh (unpublished notes, 1980-81) measured six Freeman Mountain sandstone units totaling 6,350 feet (1,935 m) interbedded with about 3,900 feet (1,190 m) of Curry Peak siltstone. These interbedded relations and poor exposures preclude mapping the units separately in the Center Creek quadrangle. About the only good exposures in the quadrangle are on the southwest-trending spur in the SW$^1/_4$ section 14 and the SE$^1/_4$ section 15, T. 5 S., R. 5 E.

The Freeman Mountain sandstone facies consists of yellowish-brown, blocky weathering, medium- to thick-bedded, commonly bioturbated, fine- to medium-grained, normally calcareous, feldspathic sandstone. The sandstone contains small amounts of pyrite, which is oxidized to goethite in outcrop. Both vertical burrows and tracks parallel to bedding planes are common. A few beds of pebble-size, subangular rip-up clasts interbedded with the finer grained sandstones are present. Uncommon beds contain reworked crinoid and fusilinid fossils that weather out to leave pits on the surface. The sandstones are less siliceous than the Pennsylvanian sandstones, and weather to more rounded, less fractured exposures.

The Curry Peak siltstone facies consists of laminated to thin-bedded, pyritic, commonly bioturbated, dark-gray siltstone with common ripple cross-stratification. In thin section, the siltstones show discontinuous films of inert organic material. In the Center Creek quadrangle, the best exposures of Curry Peak strata are immediately above the Wolfcampian limestone unit in the NW$^1/_4$SE$^1/_4$SE$^1/_4$ section 15, T. 5 S., R. 5 E.

Jurassic

Nugget Sandstone (Jn)

The Nugget Sandstone and correlative sandstone formations are renowned as one of the world's largest coastal and inland paleodune fields, which covered much of what is now Utah and portions of adjacent states in the Early Jurassic (Blakey and others, 1988). These sandstones are known too for their great thickness and uniformity. Except for a basal transitional zone and rare, thin, planar interdune deposits, they consist entirely of massively cross-bedded, fine- to medium-grained, commonly bimodal, quartz sandstone that weathers to bold, rounded cliffs.

An incomplete section of the Nugget Sandstone is exposed along the Lake Creek drainage at the north margin of the quadrangle. The Nugget Sandstone consists primarily of moderately well-cemented, well-rounded, frosted quartz grains. It is uniformly colored moderate reddish orange to moderate orange pink, although the uppermost part is generally white to very pale orange. Cementation is variably calcareous or siliceous, but the white upper part is commonly noncalcareous. The Nugget Sandstone is variably jointed, with the dominant joints trending northwest. Locally, sand grains eroded from Nugget outcrops are redeposited in small, thin sheets of eolian sand.

Along the north side of Lake Creek, the Nugget Sandstone forms a deeply dissected, near-dip slope. The base of the formation is not exposed in the Center Creek quadrangle. Southerly dips apparently lessen to the north in the adjacent Francis quadrangle, because the outcrop belt appears wider than it should be. The Nugget Sandstone is 1,306 feet (398 m) thick in the West Daniels Land #1 well; assuming a 15-degree westerly dip determined from seismic data, the stratigraphic thickness of the Nugget is about 1,260 feet (385 m). Baker (1976) reported 1,500 feet (460 m) of Nugget Sandstone west of Charleston, about 16 miles (26 km) west of the Center Creek quadrangle. The Nugget Sandstone thins both to the north and east along the flanks of the Uinta uplift (Bryant, 1992).

The upper contact with the Twin Creek Limestone, the J-2 unconformity of Pipiringos and O'Sullivan (1978), is well exposed south of Lake Creek in the SE$^1/_4$NE$^1/_4$NE$^1/_4$ section 7 and the NW$^1/_4$NW$^1/_4$ section 8, T. 4 S., R. 6 E. The contact is marked by a prominent change in lithology, with dark-reddish-brown siltstone and jasperoid and brown to gray limestone of the Gypsum Spring Member of the Twin Creek Formation overlying the planated surface of the white, massively cross-bedded Nugget Sandstone.

Twin Creek Limestone (Jtc)

The Twin Creek Limestone is divided into seven members in northern Utah: in ascending order these are the Gypsum Spring, Sliderock, Rich, Boundary Ridge, Watton Canyon, Leeds Creek, and Giraffe Creek Members (Imlay, 1967). The lower five members are each lithologically consistent and easily recognizable over a wide area. The upper two members are identifiable to the east (Coogan and Constenius, 2000), but when traced southward they lose identity and grade into the Arapien Shale (Imlay, 1967, 1980; Sprinkel, 1982, 1994). Although individual members were not mapped due to limited exposures, the lower five members can be identified in exposures south of Lake Creek. The best exposures are in the ravine in the NE¼SE¼NE¼ section 7 and the NW¼SW¼NW¼ section 8, T. 4 S., R. 6 E.

D.A. Sprinkel and H.H. Doelling (Utah Geological Survey, written communication, August 2, 1999) measured an incomplete section of 608 feet (185 m) of Twin Creek strata south of Lake Creek, and it is from their work that the following description is largely derived. The Gypsum Spring Member is 83 feet (25 m) thick and is marked at the base by a 10-foot-thick (3 m), slope-forming, dark-reddish-brown, sandy, calcareous siltstone with thick beds or boulder-size blocks of reddish- and yellowish-brown jasperoid. The jasperoid is overlain by about 16 feet (5 m) of medium-bedded, pinkish-brown, medium- to coarsely crystalline sideritic limestone with veinlets of siderite and calcite, which is in turn overlain by about 57 feet (17 m) of medium-bedded, brown to gray, dense, very fine-grained limestone with a conchoidal fracture. The Sliderock Member is 209 feet (64 m) thick and consists of brownish-gray, light-gray-weathering, slope-forming, thin- to medium-bedded, dense limestone with a conchoidal fracture; light-gray micritic limestone that weathers to pencil-like fragments; and medium-gray, dense, very fine-grained limestone with disarticulated *Isocrinus* sp. (formerly *Pentacrinus*) columnals and fossil hash near the top. The Rich Member is 116 feet (35 m) thick and consists of medium-gray, thin- to medium-bedded, finely crystalline, ledge- and slope-forming limestone that weathers to pencil-like fragments and small chips, and very light-gray, very fine-grained calcareous sandstone with ripple marks. The Boundary Ridge Member is 145 feet (44 m) thick and consists of interbedded, red-brown siltstone and fine-grained sandstone and gray to brown, sandy oolitic limestone and algal-laminated limestone that forms reddish slopes. Only the lower 55 feet (17 m) of the Watton Canyon Member is exposed, but Sprinkel and Doelling estimated the member to be about 250 feet (76 m) thick. The Watton Canyon Member consists of yellowish-gray to medium-gray, oolitic limestone and dense, very fine-grained limestone, commonly with a conchoidal or rectilinear fracture.

The Twin Creek Limestone is Middle Jurassic (middle to late Bajocian to Callovian) in age and was deposited in warm, shallow-marine waters in the south end of a north-trending foreland basin during the first two major Mesozoic transgressive episodes in west-central North America (Imlay, 1967, 1980). In the Center Creek quadrangle, the Twin Creek Limestone is unconformably overlain by the Keetley Volcanics. Regionally, the Twin Creek Limestone is conformably overlain by the Pruess Sandstone and correlative strata (Imlay, 1980).

Cretaceous

Frontier Formation, undifferentiated (Kfu)

We mapped strata herein assigned to the undifferentiated Frontier Formation (usage of Molenaar and Wilson, 1990) in widely separated exposures in the Center Creek drainage. Welsh (unpublished notes, 1980-81) was the first to recognize all but the easternmost of these generally poorly exposed, southwest-dipping beds in his unpublished mapping of the Center Creek quadrangle during the early 1980s. Lacking fossils or age estimates, he interpreted them as the early Tertiary Wasatch Formation. Hintze (1980) showed one of these exposures as a window through the Charleston thrust, probably based on misidentification of the southwest-dipping beds as Mesozoic strata and the quartzite-boulder deposits as Oquirrh bedrock. Bryant (1992) first mapped the small, but critical, easternmost outcrop in the Center Creek quadrangle as undifferentiated Cretaceous strata and correlated it with the Mesa Verde Formation and/or the Frontier Member of the Mancos Shale. As described below, we now believe these strata belong to the early Late Cretaceous Frontier Formation.

Because outcrops are widely spaced and exposures generally poor, and due also to proximity to the Charleston thrust which truncates these strata, the vertical succession of beds in this outcrop belt is uncertain. The following are lithologic descriptions based on outcrop locations. The westernmost, and some of the best, exposures are in the south-central portion of section 19, T. 4 S., R. 6 E. In a small road cut in the SW¼SE¼SW¼ section 19, Cretaceous beds are in fault contact with brecciated, northeast-dipping Wallsburg Ridge strata. The contorted Cretaceous beds consist of light-olive-gray to grayish-olive calcareous mudstone with granule-size, irregularly shaped calcareous nodules; grayish-orange to dusky-yellow calcareous siltstone; and moderate-reddish-orange, calcareous, very fine-grained silty sandstone. For a distance of about 1,000 feet (300 m) northeast up the drainage, strata are very poorly exposed but appear to consist almost entirely of dark-reddish-brown mudstone and lesser siltstone that is mottled yellowish gray to light olive gray; these beds weather to reddish slopes with slightly swelling soils. Farther upslope, but down section, very pale-orange, grayish-orange, pale-red, and light-gray mudstone is interbedded with fine- to medium-grained, calcareous quartz sandstone that is deeply weathered and mostly covered by quartzite-boulder colluvium. This is in turn underlain by a thin, less than 1-foot-thick (0.3 m), light-gray limestone bed with poorly preserved, discontinuous algal stringers, and lenses and veins of chalcedony, which is exposed at the common border of the NE¼NE¼SW¼ section 19 and the SE¼NE¼SW¼ section 19. In the NE¼NE¼SW¼ section 19 and the NE¼SW¼SE¼ section 19, a grayish-orange-pink to pale-yellowish-orange, calcareous, medium- to thick-bedded, very fine- to fine-grained quartz sandstone and somewhat darker and coarser pebbly sandstone forms low ledges. The clasts are well-rounded quartzite, chert, and minor limestone pebbles to uncommon small cobbles. Most quartzite is light brown to white with fewer greenish-gray, red, or banded red and white clasts. Still farther up the drainage, reddish-brown mudstone is exposed in a small historical landslide in the SE¼NE¼SE¼ section 19. Exposures in sections 28, 29, and 33 contain similar lithologies, but lack the thin limestone bed. No fossils were found in these beds, and four samples from these outcrops failed to produce palynomorphs.

Fossiliferous strata were found, however, in outcrops in the south-central portion of section 34, T. 4 S., R. 6 E., the outcrop that Bryant (1992) first located. Beds there form prominent, southwest-dipping strike ledges that stand in stark contrast to surrounding morainal deposits. A 6-foot-thick (2 m) oyster coquina limestone bed dips 32 degrees southwest. About 40 feet (12 m) of section is exposed stratigraphically below this oyster coquina in the main scarp of a small, historical slump. A well-cemented, very thick-bedded, very pale-orange to grayish-orange, fine-grained, noncalcareous sandstone at least 6 feet (2 m) thick is exposed at the base of the slope. This sandstone is overlain by a brownish-black, noncalcareous, soft shale that contains *Corbula* sp. bivalve, rare fish scale, and uncommon gastropod fossils (appendix). Palynologist Gerald Waanders identified angiosperm pollen (*Tricolporopollenites granulocuneus*) from this bed which suggests a Cenomanian to Turonian age (sample CC7899-1, appendix). However, the abundance of *Classopollis classoides* pollen and the dinoflagellate cysts suggest an age older than Turonian. Therefore, he suggested an age of middle to late Cenomanian for sample CC7899-1. Only about the lower 3 feet (1 m) of this black shale interval is exposed, but it may be up to about 8 feet (2.5 m) thick.

This shale bed is overlain by about 35 feet (11 m) of grayish-orange to moderate-yellowish-brown, calcareous, fine-grained silty sandstone with abundant gastropod and bivalve fossils that grades into the overlying oyster coquina (appendix). Sample CC7899-2 from the middle of this interval also yielded angiosperm pollen and dinoflagellate cysts suggesting a Cenomanian to Turonian age (appendix). Again, the abundance of *Classopollis classoides* pollen and the dinoflagellate cysts led Waanders to suggest an age of middle to late Cenomanian age for sample CC7899-2. However, the abundant gastropod and bivalve fossils from this interval – including the brackish-water gastropod *Craginia coalvillensis* (Meek, 1873) and other taxa in total – indicates an early Turonian age as this faunal list represents almost the entire fauna reported under the main coal seam at Coalville, Utah, which is in the lower Turonian Coalville Member of the Frontier Formation (Ryer, 1975, 1977; Eaton and others, 2001). The Coalville strata are now dated as early Turonian on the basis of the occurrence of the inoceramid bivalve *Mytiloides goppelnensis* (*Mytiloides opalensis* of previous authors) above and below the Coalville Member (Ryer, 1975, 1977; Kauffman and others, 1993; Kennedy and others, 2000). This taxon is known to range through most of the lower Turonian from the *Vascoceras birchbyi* Zone through much of the *Mammites nodosoides* Zone (Kennedy and others, 2000).

Early Late Cretaceous strata in the Center Creek quadrangle lie between well-studied outcrops near Coalville nearly 30 miles (48 km) to the north and at Currant Creek about 5 miles (8 km) to the southeast. Strata of these distant sections lie on opposite sides of the Uinta uplift, where they are known by different names (Molenaar and Wilson, 1990). Because exposures in the Center Creek quadrangle lie south of the axis of the Uinta uplift, south-flank terminology is generally used in this report. The correlation of north- and south-flank strata is complicated by rapid facies changes and the absence of Cretaceous outcrops across the western projection of the Uinta uplift. Still, Molenaar and Wilson (1990) clearly show that the Frontier Formation thickens greatly to the northwest, from about 760 feet (230 m) at Currant Creek to 7,800 feet (2,380 m) near Coalville. However, they also noted that the Frontier Formation in the Coalville area includes strata both somewhat older and younger than that of Frontier Formation strata on the south flank of the Uinta uplift.

Our preferred age of early Turonian corresponds to the lower Frontier Formation and likely includes strata equivalent to the Coalville Member, which is present on the north flank of the Uinta Mountains. The scarcity of exposed Cretaceous strata and lack of fossils elsewhere in the Center Creek quadrangle prevents us from further subdividing early Late Cretaceous strata.

Bivalves and gastropods recovered from the south-central portion of section 34, T. 4 S., R. 6 E. are a mixture of brackish and shallow-marine taxa. Together with the absence of inoceramid bivalves and ammonites, which are restricted to open-marine conditions, these shelly beds are thought to indicate a subsaline environment, perhaps representing a large coastal bay (James I. Kirkland, Utah Geological Survey, written communication, April 16, 2001; see also Fursich and Kirkland, 1986; Fursich, 1994; and Kirkland, 1996).

Cretaceous strata in the Center Creek quadrangle are incompletely exposed across a belt up to 3,500 feet (1,070 m) wide. They are unconformably overlain by the Keetley Volcanics and Quaternary deposits. Given an average 30 degree southwest dip (see plate 1), the maximum exposed thickness of Cretaceous strata in the Center Creek quadrangle is about 1,750 feet (530 m). An incomplete section of Cretaceous strata is about 2,500 feet (760 m) thick along the line of cross section A-A′.

Tertiary

Uinta(?) Formation (Tu?)

In the Center Creek quadrangle, the Uinta(?) Formation is a very poorly exposed, subrounded to rounded, pebble- to boulder-conglomerate that weathers to a residual boulder field. Because the clasts appear to be almost entirely Oquirrh orthoquartzite and sandstone, it can be difficult to distinguish these deposits from poorly exposed Permian bedrock, which it unconformably overlies. Neither Baker (1976) nor Bryant (1992) mapped these deposits in the Center Creek quadrangle, although they did map apparently correlative deposits by different names a few miles to the south in the Twin Peaks quadrangle. In his unpublished mapping of the Center Creek, Charleston, Co-op Creek, and Twin Peaks quadrangles, Welsh suggested that these deposits are alluvial-fan facies of the Uinta Formation. Because only a small, poorly exposed portion of these deposits is in the Center Creek quadrangle, we chose to query the name pending further studies. Based on map patterns, only the lower 350 feet (110 m) of the formation is present in the Center Creek quadrangle. The Uinta Formation is Eocene in age (Dane, 1954).

Keetley Volcanics

The Keetley Volcanics are late Eocene to early Oligocene volcanic breccias, conglomerates, tuffs, lava flows, and intrusives that rest subhorizontally in a structural saddle between the Wasatch Range and Unita Mountains. The Keetley Volcanics are regionally divided into three lithologic units: a basal unit of fine-grained tuff, lapilli tuff, thin lahar deposits, and volcaniclastic sandstone and conglomerate at least locally deposited in a lake; a middle, thick unit of volcaniclastic conglomerate and breccia; and an upper unit of lava flows (Leveinen, 1994; Bryant, 1992). Parts of the lower two units are recognized in the Center Creek quadrangle, which we here divide into three informal units. Keetley strata are andesite and rhyodacite by field classification, but chemically range from trachyandesite and latite to silica-poor rhyodacite (Bromfield and others, 1977; Hanson, 1995; Feher, 1997; Vogel and others, 1997).

The Keetley Volcanics lie at the east end of the east-west-trending, 28-mile-long (45 km) Wasatch intrusive belt. As described by John (1987, 1989a), Hanson (1995), Feher (1997), and Vogel and others (1997), several Tertiary intrusives are in the high-potassium, calc-alkaline rocks of the Wasatch intrusive belt. From west to east these include three phaneritic stocks (Little Cottonwood, Alta, and Clayton Peak), five porphyritic stocks (collectively known as the Park City porphyries), the Park Premier porphyry, and the Indian Hollow plug. With the exception of the slightly older, more mafic Clayton Peak stock, the silica content of the plutons generally increases to the west (Hanson, 1995), and the depth of emplacement of the exposed portion increases to the west, from less than 0.6 mile (less than 1 km) for the porphyritic Park Premier and Indian Hollow intrusions to about 6.5 miles (11 km) for the phaneritic Little Cottonwood stock (John, 1987, 1989a). The entire belt is probably between 33.5 and 36.6 million years old based on biotite ages, except the Little Cottonwood stock, which is 30.5 ± 0.5 Ma (Vogel and others, 1997). Keetley strata are intruded both by the Park Premier porphyry, which consists of five granodiorite to rhyodacite or dacite porphyry intrusions and is the center of a several-square-kilometer area of hydrothermal alteration and precious-metal mineralization (Willes, 1962), and the Indian Hollow plug, a volcanic neck surrounded by a radial dike swarm (Bromfield, 1968; Woodfill, 1972; Hanson, 1995). The Indian Hollow plug and Park Premier porphyry may be the source of most of the Keetley Volcanics (Bromfield, 1968; Woodfill, 1972; John, 1989b; Bryant, 1992; Leveinen, 1994; Hanson, 1995; Feher and others, 1996; Feher, 1997).

Published potassium-argon ages of biotite or hornblende from Keetley flows range from 33.6 ± 1.0 to 37.5 ± 1.3 Ma (Crittenden and others, 1973; Bromfield and others, 1977; Bryant, 1990). Kurt Constenius (written communication, March 8, 2001) reported $^{40}Ar/^{39}Ar$ plateau ages on biotite from the lowest Keetley tuffs in the Strawberry Reservoir area and at Currant Creek Peak of 37.25 ± 0.14 Ma and 37.73 ± 0.28 Ma. What are likely Keetley tuffs near Peoa contain early Oligocene vertebrates (Nelson, 1971).

Most Keetley clasts contain 15 to 25 percent hornblende and 25 to 35 percent plagioclase phenocrysts as major phases with minor biotite and clinopyroxene (Leveinen, 1994; Feher, 1997). Hanson (1995) and Feher (1997) noted that Keetley strata exhibit a wide range in chemical composition. Feher (1997) noted that compared to other well-documented calc-alkaline rocks, the Keetley Volcanics do not follow typical calc-alkaline chemical trends nor do they follow simple crystal fractionation or assimilation paths.

The Keetley Volcanics are in excess of 1,650 feet (500 m) thick north of Heber City (Bryant, 1992; Leveinen, 1994). In the Center Creek quadrangle, map patterns suggest that the Keetley Volcanics are locally in excess of 2,500 feet (760 m) thick. In the Center Creek quadrangle just south of Lake Creek, the Keetley Volcanics unconformably overlie Nugget and Twin Creek strata. To the south in the Center Creek drainage, Keetley strata unconformably overlie Cretaceous beds and the Oquirrh Formation. The Keetley Volcanics were deposited in an area of considerable pre-Keetley topography (Boutwell, 1912; Forrester, 1937, O'Toole, 1951; Woodfill, 1972; Feher, 1997).

Tuffaceous unit (Tkt): With one exception, the tuffaceous unit is present only north of Center Creek where it is nearly everywhere covered by colluvium and residual debris from the overlying quartzite-boulder unit and so is very poorly exposed; it is part of the regional, lower tuffaceous unit. Test pits excavated by others in the NW1/4 section 13, T. 4 S., R. 5 E. show that the tuffaceous unit is at least locally covered by quartzite-boulder colluvium in excess of 7 feet (2 m) thick. Even so, soils developed on the tuffaceous unit tend to be white and poorly drained.

The following description is based on just a few road-cut exposures in the SE1/4 section 13 and the NE1/4 section 24, T. 4 S., R. 5 E., and in the SW1/4SW1/4NW1/4 section 19, T. 4 S., R. 6 E., and two natural exposures in the SE1/4SW1/4NE1/4 section 19 and the NE1/4NW1/4SW1/4 section 20, T. 4 S., R. 6 E. Road cuts in sections 13 and 24 reveal very light-gray, light-olive-gray, and light-brownish-gray, very fine-grained tuffaceous mudstone with uncommon, medium-sand-size biotite flakes. The small exposure in section 19 is light-olive-gray to yellowish-gray, fine-grained lapilli tuff with altered, granule-size pumice fragments and similarly colored, medium- to coarse-grained, tuffaceous and pebbly sandstone with subangular quartzite clasts. The two natural exposures immediately underlie the quartzite-boulder unit, about 600 to 800 feet (180-245 m) above these road-cut exposures. They consist of both fine- and coarse-grained tuff and tuffaceous sandstone.

Deposits mapped in the lower reaches of Clegg Canyon consist of white to pinkish-gray to very pale-orange, thick- to very thick-bedded, moderately cemented, calcareous, tuffaceous sandstone and matrix-supported pebbly sandstone. The clasts are subangular to subrounded, white, calcareous and tuffaceous mudstone rip-up clasts and clasts of Oquirrh Formation orthoquartzite. The best exposures are in the SE1/4 section 8, T. 5 S., R. 6 E.

The tuffaceous unit appears to pinch out against Twin Creek strata in the northeast corner of the Center Creek quadrangle, in the W1/2 section 8, T. 4 S., R. 6 E. The nature of this apparent pinchout is uncertain, but it appears to be at least in part fault controlled based on offset of the Nugget Sandstone and Twin Creek Limestone. It may also reflect abrupt thinning of lower Keetley strata over a paleohigh of Twin Creek and Nugget strata, or erosion of the tuffaceous unit prior to deposition of the volcanic breccia of Coyote Canyon. The tuffaceous unit varies from 0 to at least 720 feet (0-220 m) thick.

Quartzite-boulder unit (Tkq): The quartzite-boulder unit forms a coarse, clastic wedge that thins to the northeast in the Center Creek quadrangle; it is part of the regional, middle volcaniclastic conglomerate and breccia unit. Because it lacks volcanic clasts, the unit contrasts sharply with the enclosing tuffaceous and volcaniclastic units of the Keetley Volcanics.

The quartzite-boulder unit consists of two distinct but unmapped facies. The vast majority of the unit forms slopes and locally broad benches covered by subangular to subrounded pebbles, cobbles, and boulders of Oquirrh Formation orthoquartzite and uncommon limestone derived from the Charleston allochthon to the southwest. Two areas, however, contain mostly Mesozoic clasts. Much of the area between the Center Creek and Lake Creek drainages that we map as the quartzite-boulder unit was shown as Oquirrh strata on previous geologic maps (Baker, 1976; Hintze, 1980; Bryant, 1992), probably because of a predominance of orthoquartzite clasts. Bryant (1992) first mapped some of these deposits as an Oligocene-Eocene quartzite conglomerate and correlated them with similar deposits along the south flank of the Uinta Mountains.

The quartzite-boulder unit is nowhere well exposed, but it tends to form broad benches above colluvium-covered slopes of the tuffaceous unit. We found only a few small consolidated outcrops of the quartzite-boulder unit in the Center Creek quadrangle. Clasts at the surface are commonly fractured so that the deposits appear more angular than they actually are. The quartzite-boulder unit locally contains large, brecciated blocks of Oquirrh Formation orthoquartzite up to 200 feet (60 m) in length. One block is at the common border of sections 20 and 29, T. 4 S., R. 6 E., about 1,100 feet (335 m) west of the east section line. The other block is in the NW1/4SE1/4NE1/4SE1/4 section 18, T. 4 S., R. 6 E. These large blocks are 1 mile (1.6 km) or more northeast of upper-plate strata and suggest a steep mountain front was present to the southwest in late Eocene to early Oligocene time.

On the drainage divide between Lake Creek and Center Creek, in the NE1/4SE1/4 section 18, T. 4 S., R. 6 E., SE1/4 section 12, T. 4 S., R. 5 E., and the SW1/4 section 7, T. 4 S., R. 6 E., the quartzite-boulder unit consists principally of subangular to subrounded clasts of Thaynes Limestone (Lower Triassic) and Nugget Sandstone (Lower Jurassic); clasts possibly from Park City (Permian), Woodside (Lower Triassic), and Twin Creek (Middle Jurassic) strata; and locally orthoquartzite clasts derived at least in part from the Oquirrh Formation. Limestone clasts are typically rounded and volcanic clasts appear to be absent. Boulders up to 10 feet (3 m) in diameter are present. These clasts were probably derived from the north and northwest, or possibly from the southeast, based on distribution of source rocks. Similar clasts are present in the overlying basal volcanic breccia of Coyote Canyon.

The contact with the volcanic breccia of Coyote Canyon appears sharp, and corresponds to the first appearance of volcanic clasts. The lower contact of the quartzite-boulder unit with the tuffaceous unit is difficult to determine in most areas. Where the quartzite-boulder unit forms broad benches, the contact is marked by a change in slope, with the quartzite-boulder unit forming steeper slopes. The quartzite-boulder unit varies from 0 to about 450 feet (0-140 m) thick.

Volcanic breccia of Coyote Canyon (Tkb): The volcanic breccia of Coyote Canyon, named by Bromfield and others (1970) for exposures at Coyote Canyon north of Heber City, is widely exposed on the drainage divide between Center Creek and Lake Creek; it is part of the regional, middle volcaniclastic conglomerate and breccia unit. It is also present in the Center Creek drainage and in fault blocks at the east end of Hogsback Ridge. This unit consists principally of volcaniclastic boulder deposits that grade upward into coarse volcanic breccias. These deposits generally form slopes with abundant volcanic clasts, and in the Center Creek quadrangle, good exposures are restricted to road cuts. Limited bedding attitudes and interpretation of aerial photographs show that the volcanic breccia of Coyote Canyon dips gently north, toward the inferred source of the volcanic debris.

The basal part of the volcanic breccia of Coyote Canyon locally contains subrounded to rounded Oquirrh-like orthoquartzite clasts, as well as clasts from the Nugget, Thaynes, Woodside, and Park City(?) Formations. Such clasts become rare immediately upsection, where deposits consist almost entirely of coarse volcaniclastic boulder deposits (figure 3). These deposits grade upward into rhyodacitic to andesitic tuff breccias and coarse volcanic breccias. We identified a single marker bed in the northeast part of the quadrangle. It is a ledge-forming, gray- to red-weathering, andesitic flow breccia about 20 feet (6 m) thick.

At the east end of Hogsback Ridge, the volcanic breccia of Coyote Canyon locally contains abundant orthoquartzite and uncommon limestone clasts, thus suggesting that these deposits represent the basal part of the unit. Deposits in the Mud Spring and Cold Spring areas are thin and identified only by the occurrence of rounded volcanic cobbles and boulders. Soils developed on these deposits tend to be a deeper, richer brown compared to soils developed on Oquirrh Formation strata, and desiccation cracks show that they exhibit a slight shrink-swell potential. On the ridge east of the Hogsback enclosure, orthoquartzite clasts predominate and volcanic clasts are rare. Near the center of section 3, T. 5 S., R. 6 E., about 2,000 feet (600 m) north of the south sec-

Figure 3. *Volcanic breccia of Coyote Canyon exposed in cliff face at head of cirque, section 22, T. 4 S., R. 6 E., Heber Mountain quadrangle. Hammer is at intraformational contact between two thick debris-flow beds that fine upward.*

tion line at an elevation of about 9,200 feet (2,805 m), a well-cemented, calcareous, subrounded, clast-supported, pebble to boulder conglomerate is exposed that consists of Oquirrh Formation orthoquartzites and uncommon limestones. Bedding is uncertain but probably subhorizontal. This orthoquartzite conglomerate may represent a tongue of the underlying quartzite-boulder unit described above, or may represent a younger, later Tertiary boulder deposit.

The volcaniclastic deposits of the lower part of the volcanic breccia of Coyote Canyon probably represent debris flows (Leveinen, 1994). These deposits lack gas-escape structures, bombs, and welded or agglutinated clasts, and do not show facies associations typical of lag-fall breccias or other co-ignimbrite breccias (Leveinen, 1994). The volcanic breccia of Coyote Canyon varies from 0 to more than 1,400 feet (0-430 m) thick; the top of the unit is not preserved in the Center Creek quadrangle.

Keetley Volcanics, undifferentiated (Tku): We did not assign a subunit name to a low hill of Keetley Volcanics north of Lake Creek in the northwest corner of the quadrangle. The deposits are poorly exposed and contain a mixed clast assemblage of subrounded volcanic and orthoquartzite pebbles to boulders. The deposits are about 80 feet (24 m) thick in the Center Creek quadrangle. The deposits may belong to the volcanic breccia of Coyote Canyon, but they are at a topographically lower elevation than such deposits to the south. Future mapping in the adjacent Francis quadrangle may resolve the stratigraphic position of these deposits.

Alluvial Deposits (Ta)

We mapped a single exposure of moderately sorted, unconsolidated, sand- to boulder-size sediment of uncertain, probable late Tertiary age at the northwest end of Hogsback Ridge. This deposit lies 1,300 feet (400 m) above the floor of Daniels Canyon and contains subrounded Keetley volcanic and Oquirrh Formation orthoquartzite boulders to about 10 feet (3 m) in diameter. Baker (1976) mapped this deposit as a Tertiary intrusive, and assumed that the orthoquartzite boulders were imbedded in the "plug," although he admitted uncertainty in that interpretation. The size of the clasts and their bimodal lithology strongly supports a debris-flow or reworked debris-flow origin for this deposit. The deposit could belong to the basal part of the volcanic breccia of Coyote Canyon, which also typically contains a mixed clast assemblage, but its isolation precludes confident correlation. These deposits cap Hogsback Ridge and are up to a few feet thick.

Quaternary and Tertiary

Alluvial-Fan Deposits (QTaf)

Alluvial-fan deposits of uncertain Quaternary to late Tertiary age are present in Daniels Canyon and in the Center Creek drainage. The deposits in Daniels Canyon are generally 800 to 1,500 feet (245-460 m) above Daniels Creek where they were deposited in the broad, ancestral paleovalley of Daniels Canyon (figure 4). These alluvial-fan deposits consist almost exclusively of poorly sorted, locally derived, clay- to boulder-size sediment that forms a moderately sloping apron on the flank of the Oquirrh highland to the south. On the south side of Daniels Canyon, near and northwest of Boomer Canyon, the clasts consist entirely of subangular Oquirrh Formation orthoquartzite and rare limestone. Deposits in the SW1/4 section 35, T. 4 S., R. 5 E. are locally underlain by a poorly exposed, calcareous, coarse-grained, pebbly sandstone with orthoquartzite and deeply weathered tuffaceous clasts. These deposits probably represent channel deposits that were buried by alluvial fans. The alluvial-fan deposits can look remarkably similar to Oquirrh bedrock and unmapped regolith, but are distinguished by having a slightly more diverse assemblage of Oquirrh Formation orthoquartzites and sandstones than typical bedrock exposures, and by their subtle geomorphic expression. Deposits between Clegg and Center Canyons (section 17, T. 5 S., R. 6 E.) contain mixed orthoquartzite and volcanic clasts and may belong to the quartzite-boulder unit or the lower part of the volcanic breccia of Coyote Canyon. These deposits in Daniels Canyon range up to about 50 feet (15 m) thick.

Old alluvial-fan deposits southwest of the mouth of Center Creek canyon are compositionally and morphologically similar to those on the south side of Daniels Canyon. These deposits appear to overlie the volcanic breccia of Coyote Canyon. These deposits are also up to about 50 feet (15 m) thick.

Quaternary

Alluvial Deposits

Old alluvial deposits (Qao): We mapped a single exposure of moderately sorted sand and pebble to small-boulder grav-

Figure 4. *Oblique aerial view to west-northwest of the broad, ancestral paleovalley above and parallel to Daniels Canyon. Row Hollow, in the adjacent Twin Peaks quadrangle, is at the lower left of the photograph. Photograph taken by Welsh in 1981.*

el in the lower reaches of Daniels Canyon (SE1/4 section 35, T. 4 S., R. 5 E.) that lies about 300 to 400 feet (90-120 m) above the valley floor. These deposits contain subrounded orthoquartzite and limestone clasts derived from the Oquirrh Formation. The lower part of the deposit contains subrounded, calcareous, light-brown, medium- to coarse-grained, pebbly and tuffaceous sandstone cobbles probably derived from the tuffaceous unit of the Keetley Volcanics, and subangular to subrounded, Oquirrh Formation orthoquartzite clasts. The diversity and rounding of clasts suggests that these deposits are channel deposits derived from upstream sources. The deposits are probably less than about 20 feet (6 m) thick and are Pleistocene in age. Similar though less well-exposed deposits may be present beneath alluvial-fan deposits (QTaf) in the SW1/4 section 35, T. 4 S., R. 5 E.

Valley-fill deposits (Qa_2, Qa_3): Valley-fill deposits in the eastern part of Heber Valley form a gently west-sloping surface little dissected by Daniels, Center, and Lake Creeks. These deposits consist of moderately sorted sand, silt, and pebble to boulder gravel probably deposited in part by braided streams choked with glacial outwash. Level 3 deposits are preserved as a low terrace above level 2 deposits at the eastern end of Heber Valley. Excavations for a Central Utah Project water facility just west of the Center Creek quadrangle (in sediments correlative with our Qa_2 deposits) revealed moderately well-developed, secondary calcium carbonate in the upper part of the deposit (Stage II to II+ carbonate of Birkeland and others, 1991). The thickness of valley-fill deposits in the Center Creek portion of Heber Valley is uncertain but probably less than about 100 feet (30 m) (Peterson, 1970; Roark and others, 1991). Soil profiles reported by Sullivan and others (1988) suggest a latest Pleistocene age for much of the alluvial surface in Heber Valley. Our level 2 deposits likely contain Holocene sediment at least along the main drainages.

Stream-terrace deposits (Qat_2, Qat_3): We mapped stream-terrace deposits only along Daniels Creek and Lake Creek, where they form level to gently sloping alluvial surfaces above the modern flood plain. These deposits consist of moderately to well-sorted sand, silt, clay, and pebble to boulder gravel deposited principally in river-channel and flood-plain environments. The deposits locally include small alluvial-fan and colluvial deposits adjacent to nearby steep slopes. The subscript denotes the relative age and height above the modern drainages: level 2 deposits are about 10 to 35 feet (3-11 m) and level 3 deposits are 35 to 60 feet (11-18 m) above modern drainages. Level 2 deposits along Lake Creek are generally 25 to 35 feet (7.5-11 m) above the modern drainage and are of probable glacial outwash origin. Stream-terrace deposits range up to about 45 feet (14 m) thick and are incised by alluvial deposits (Qal_1). Stream and terrace profiles constructed for Daniels Creek show that level 3 deposits may be correlative with, and in part older than, level 2 and 3 valley-fill deposits (Qa_2 and Qa_3) of the east end of Heber Valley. Stream-terrace deposits are probably late Pleistocene in age.

Alluvial deposits (Qal_1): Alluvial deposits are present along Daniels Creek, Center Creek, and Lake Creek, the three principal drainages in the quadrangle. They consist of moderately to well-sorted sand, silt, clay, and pebble to boulder gravel normally less than about 20 feet (6 m) thick. Alluvial deposits include river-channel and flood-plain sediments, and minor terraces up to about 10 feet (3 m) above current stream levels; small alluvial-fan and colluvial deposits too small to map separately are included in this map unit. Alluvial deposits are Holocene in age and are gradational with mixed alluvial and colluvial deposits.

Alluvial mud (Qam): Localized areas of alluvial mud are present on the surface and along the margins of ground moraine. These deposits, which accumulated in shallow depressions and swales following ice retreat, consist of dark-gray-brown clay and silt with abundant organic matter and are probably less than about 5 feet (2 m) thick. They are believed to be latest Pleistocene to Holocene in age.

Older alluvial-fan deposits (Qafo): Older alluvial-fan deposits form the deeply incised eastern margin of Round Valley in the southwest corner of the quadrangle, and they also form isolated surfaces high above the modern drainages of Daniels and Lake Creeks. The fan deposits consist of poorly to moderately sorted, non-stratified, boulder- to clay-size sediment derived from upgradient drainage basins and thus vary in clast composition. Deposits in Round Valley and Daniels Canyon consist of subangular Oquirrh Formation orthoquartzite and lesser limestone clasts. The deposits of Round Valley are displaced by the Round Valley fault, described later. The thickness of the older alluvial-fan deposits in the Round Valley portion of the Center Creek quadrangle is uncertain, but Sullivan and others (1988) reported that unconsolidated valley-fill deposits are up to 180 to 215 feet (55-60 m) thick in the eastern part of Round Valley, just west of the quadrangle. The older alluvial-fan deposits in Daniels Canyon cover a broad bench about 200 to 300 feet (60-90 m) above the modern valley floor (figure 2). The thickness of these deposits is uncertain due to colluvial cover at their downslope margins, but they may be up to 100 feet (30 m) or more thick, thinning to a taper edge at their upslope margins. The upslope margin of the deposits in Daniels Canyon are commonly overlain by talus or mixed alluvial and colluvial deposits. Older alluvial-fan deposits in the Lake Creek drainage contain sediment derived from the Keetley Volcanics, and consist of poorly sorted, boulder- to sand-size volcanic clasts in a dark-gray clayey matrix. These deposits overlie the Nugget Sandstone, and typically grade downslope into colluvium. The thickness of these deposits is uncertain but is probably similar to the deposits in Daniels Canyon. Older alluvial-fan deposits are probably middle to early-late Pleistocene in age.

Level 2 alluvial-fan deposits (Qaf_2): Level 2 alluvial-fan deposits are best developed in the Center Creek drainage and along the eastern margin of Heber Valley; smaller deposits are also found in the Daniels Creek drainage. These inactive alluvial-fan deposits underlie moderately incised, gently sloping surfaces that lie a few tens of feet above modern depositional surfaces. They consist of poorly to moderately sorted, non-stratified, clay- to boulder-size sediments derived from up-gradient drainage basins. The deposits probably range up to about 50 feet (15 m) thick. Along the eastern margin of Heber Valley, these deposits are characterized by moderately well-developed secondary calcium carbonate in their upper part (Stage III carbonate development of Birkeland and others, 1991) and they appear to be truncated by valley-fill deposits (Qa_2 and Qa_3) of Heber Valley. Level 2 alluvial-fan deposits thus predate the valley-fill deposits, the latter of which are believed to represent

Pinedale-age glacial outwash deposited between about 30 and 12 ka. Level 2 alluvial-fan deposits are probably late Pleistocene in age.

Alluvial-fan deposits (Qaf_1): Active, isolated alluvial fans are common throughout the quadrangle. They consist of poorly to moderately sorted, non-stratified, clay- to boulder-size sediment deposited principally by debris flows at the mouths of active drainages. These fans are active depositional surfaces, although somewhat older sediments may be present at depth. Most modern alluvial-fan deposits are probably less than 40 feet (12 m) thick and are Holocene in age.

Artificial-fill Deposits (Qf)

Artificial fill consists principally of local borrow material used in the construction of small stock and retaining ponds throughout the Center Creek quadrangle. Most of the larger structures in the Center Creek and Lake Creek drainages were built to raise the level of existing small ponds already present on pre-existing morainal topography. We mapped only the larger fill deposits, although fill is common in "built-up" areas throughout the quadrangle.

Colluvial Deposits (Qc)

Colluvial deposits consist of poorly to moderately sorted, clay- to boulder-size, locally derived sediment deposited principally by slopewash and soil creep on moderate slopes. Colluvium is common on most slopes in the quadrangle, but is only mapped where deposits are thick and extensive enough to conceal large areas of bedrock. These deposits locally include talus and mixed alluvial and colluvial deposits that are too small to be mapped separately. Colluvial deposits range up to about 30 feet (9 m) thick and are probably Holocene in age.

Glacial Deposits (Qgb?, Qgp)

Deposits associated with late Pleistocene glaciation are present in the Lake Creek and Center Creek drainages. Ground moraine consisting of lodgment and ablation till, and glaciofluvial deposits, are present in both drainages above an altitude of 6,600 feet (2,000 m). The till is widespread on the valley floors and consists of poorly sorted, non-stratified, heterogenous mixtures of clay, silt, sand, gravel, cobbles, and boulders. Clasts are subangular to well rounded and include, in order of decreasing abundance, volcanic lithologies, orthoquartzite, sandstone, and limestone. Relative clast composition varies locally, reflecting differences in source rocks. The relative abundance of fine-grained matrix also varies locally, as does the degree of consolidation; the lodgment till is typically somewhat overconsolidated as a result of being deposited directly beneath active glacial ice, and is thus more compact than the ablation till. Locally, ice-thrust bedrock blocks up to several tens of feet in length are present. Glaciofluvial deposits are present locally. Although similar in overall composition to the till, glaciofluvial deposits typically exhibit crude stratification and better sorting.

Glacial geomorphology in the Lake Creek and Center Creek drainages is represented by a variety of features. Hummocky ground moraine distinguished by numerous shallow closed depressions, many of which contain ponds or lakes, is common between altitudes of 7,000 and 7,600 feet (2,130-2,320 m). Dikes have been constructed adjacent to many of these depressions to increase the volume of impounded water (Witts Lake and Jones Reservoir, for example, in section 10, T. 4 S., R. 6 E.). Broad cirques are present at the heads of the drainages, on the adjacent Heber Mountain quadrangle. The cirque at the head of the Lake Creek drainage is better developed than its Center Creek counterpart, possibly because of differences in aspect, erodibility of the underlying bedrock, or relative degree of glacial activity. Lateral and end moraines are prominent in the Lake Creek drainage, and lateral moraines may be present in the Center Creek drainage. Especially notable are sharp-crested moraines on the north side of Lake Creek, indicating late-stage glacial activity. A narrow, lateral moraine-like ridge crosses section 5, T. 4 S., R. 6 E. on the north side of Lake Creek and is cored by Nugget Sandstone bedrock and mantled with what we interpret to be bouldery ice-marginal deposits. This ridge, along with an anomalously steep and uniformly eroded slope of Nugget Sandstone on the south side of Lake Creek, seems to indicate a narrow tongue of ice extended down the Lake Creek drainage to an altitude of 6,400 feet (1,952 m).

The glacial deposits in the Lake Creek drainage may be associated with the two most recent glaciations in the greater Rocky Mountain region: the Pinedale and Bull Lake (Blackwelder, 1915). The Pinedale glaciation is generally thought to have occurred between 12 and 30 ka (Madole, 1986), although some Pinedale end moraines may be as old as 60 to 70 ka (Coleman and Pierce, 1979; Porter and others, 1983). The Bull Lake glaciation occurred between 130 and 155 ka (Pierce and others, 1976). Bryant (1992) mapped the Lake Creek deposits as till of Pinedale age, but other workers have suggested that Bull Lake deposits may also be present (G.C. Schlenker, Kleinfelder, written communication, 1996). We obtained a conventional accelerator mass spectrometer age of 40,810 ± 310 yr B.P. on wood from borehole B-14 in the Lake Creek drainage (NW1/4SE1/4SW1/4 section 15, T. 4 S., R. 6 E.). This sample was made available by Tim Thompson of Intermountain Geoenvironmental Service. The split-spoon sample (12A) – a dense, brownish-gray, silty sand with wood fragments – was obtained from borehole B-14 at a depth of 59 feet (18 m). The sample may represent sediment and organic material that accumulated in a depression on pre-existing, hummocky topography of glacial or mass-movement origin; the age of this inferred hummocky surface is unknown. Our ^{14}C age suggests that the large, older mass movement in sections 15 and 22 was emplaced sometime after about 40 ka.

Relative criteria used to differentiate Bull Lake, or at least pre-Pinedale, deposits at the lowermost extent of the glacial deposits include degree of post-glacial ground modification, soil development, and degree of weathering of coarse-grained volcanic clasts. The Bull Lake(?) deposits (Qgb?) are morphologically subdued and have better developed surface drainage than the Pinedale deposits (Qgp). Incised stream-channel exposures of Bull Lake(?) till in the SW1/4SE1/4 section 4, T. 4 S., R. 6 E. display significant clay and secondary calcium-carbonate accumulations consistent with soil-development indices for B-horizon development in Bull Lake-aged till as described by Shroba and Birkeland (1983) (figure 5). Exposures in Pinedale deposits display

Figure 5. White, pedogenic carbonate horizon developed in till, exposed in south slope of ravine in SW1/4SE1/4 section 4, T. 4 S., R. 6 E.; note hammer for scale. The north slope of this ravine exposes a moderately well-developed Bt soil horizon. Soil development suggests till may be of Bull Lake age.

consistently weak B-horizon development. Finally, coarse-grained volcanic clasts within Bull Lake(?) deposits are typically partly to completely grussified, whereas similar clasts in Pinedale deposits are typically intact. Relative morphologic expression and local superposition of deposits indicates multiple glacial advances during both periods of glaciation, but we did not differentiate deposits associated with individual glacial stades on the geologic map.

The thickness of the glacial deposits varies dramatically. Based on topography and subsurface contact projections, the Bull Lake(?) deposits likely have a maximum thickness of about 200 feet (60 m), and the Pinedale deposits likely have a maximum thickness of 150 feet (46 m). Pinedale deposits in the Center Creek drainage appear to be thinner than those in the Lake Creek drainage, and in several areas, Cretaceous and Pennsylvanian outcrops are surrounded by thin morainal deposits. We observed no evidence for pre-Pinedale glacial deposits in the Center Creek drainage.

The Lake Creek ground moraine is largely derived from the Keetley Volcanics and is susceptible to landsliding. Hylland and Lowe (1995) interpreted a large part of the moraine area as a deep-seated landslide complex; detailed mapping, however, indicates areas that probably have not undergone post-glacial mass movement. Historical landsliding has been concentrated along the steeply incised banks of Lake Creek. The Center Creek ground moraine is also derived in part from the Keetley Volcanics, as well as from low-strength Cretaceous rocks, and so is also susceptible to landsliding. Although Bryant (1992) mapped the Center Creek Quaternary deposits as landslide deposits, soil texture and surface morphology in at least their lower extent suggest a glacial origin. However, the ground moraine thins to the east (up the valley), and differentiating moraine from landslide deposits is difficult due to scant exposures and extensive vegetative cover.

Mass-Movement Deposits

Landslide deposits (Qmso, Qmso?, Qmsy, Qmsh): We grouped landslides into older (Qmso, Qmso?), younger (Qmsy), and historical (Qmsh) landslides based on degree of preservation of characteristic features, similar to the classification proposed by McCalpin (1984). Historical landslides are characterized by hummocky topography, numerous internal scarps, chaotic bedding, and evidence of historical movement, such as tilted trees, very fresh scarps, and damaged roads, utilities, or other structures. Younger landslides are similar in character and occurrence as historical landslides, but landslide features such as scarps and slide blocks are morphologically less distinct as a result of weathering and erosion. Landslide features of older landslides are morphologically subtle or indistinguishable, and some deposits are queried.

The largest landslides in the Center Creek quadrangle involve the Keetley Volcanics and are characterized by a subdued morphology characteristic of older mass movements (Qmso). Based on the degree of preservation of characteristic landslide features, most of these mass movements probably occurred as rotational slumps in the late Pleistocene. As described above, the large mass movement in sections 15 and 22, T. 4 S., R. 6 E. was emplaced sometime after about 40 ka. Younger (including historical) landslides are also typically characterized by rotational slump, although translational movement or flow also occurs locally.

We mapped numerous historical landslides, some of which had not previously been reported. Most historical landslides in the Center Creek quadrangle have slip surfaces in glacial till, Keetley Volcanics, or Cretaceous strata, as well as colluvial and residual sediments derived from these units; the slides involve these units and overlying deposits. Their thickness is highly variable. Most of these landslides probably formed during the unusually wet years of the early 1980s, and some show signs of continued movement. We also mapped ridge-top deformation features (sackungen) in the northeast part of the quadrangle, which are described in the geologic hazards section of this report.

Talus deposits (Qmt): Talus consists of locally derived material deposited principally by rock fall on and at the base of steep slopes. These deposits consist of very poorly sorted, angular boulders and lesser fine-grained interstitial sediments. Talus is widespread over bedrock units in the Center Creek quadrangle, especially the Oquirrh Formation, but we mapped only the larger, more prominent deposits. These deposits are characterized by angular boulder fields that lack vegetation and range up to about 30 feet (9 m) thick. They are considered Holocene in age.

Mixed-Environment Deposits

Alluvial and colluvial deposits (Qac, Qaco): We mapped mixed alluvial and colluvial deposits along secondary drainages and larger swales. These deposits consist of poorly to moderately sorted, clay- to boulder-size, locally derived sediment deposited by both alluvial and colluvial processes. Mixed alluvial and colluvial deposits (Qac) are generally less than 20 feet (6 m) thick, and are considered Holocene in age. Older, inactive and deeply incised deposits (Qaco) are probably less than 40 feet (12 m) thick and are likely Pleistocene and perhaps Holocene in age.

Residual and colluvial deposits (Qrc): Mixed residual and colluvial deposits obscure bedrock throughout much of the quadrangle, but are mapped principally where they are extensive enough to conceal large areas of bedrock and bedrock contacts. Such areas commonly correspond to north-facing, densely vegetated slopes. These deposits consist of poorly to moderately sorted, clay- to boulder-size, locally derived sediment derived from in-situ weathering and modified by colluvial processes. Mixed residual and colluvial deposits range up to about 15 feet (5 m) thick and are considered Holocene in age.

Stacked-Unit Deposit

Colluvium over undifferentiated Frontier Formation (Qc/Kfu): The Frontier Formation is generally poorly exposed in the Center Creek quadrangle. It is commonly concealed by colluvial and lag deposits derived from the quartzite-boulder unit of the Keetley Volcanics, although local topography and soils indicate that Frontier strata are present at shallow depth. This colluvial cover varies from a few feet to about 10 feet (3 m) thick. We mapped this stacked unit because of the importance of Cretaceous bedrock in deciphering the structural history of the region, and because Cretaceous strata are prone to landsliding.

STRUCTURE

Regional Setting

The Center Creek quadrangle lies in a structural and topographic saddle between the Uinta Mountains and the Wasatch Range. The Uinta Mountains are a 160-mile-long (250 km) west-trending belt of mostly Middle Proterozoic rocks. Uplift of the Uinta Mountains began in the late Campanian to early Maastrichtian (about 75 million years ago) – as evidenced by growth strata of the Currant Creek Formation – and continued through the end of the middle Eocene (about 40 million years ago) (Kurt Constenius, written communication, March 8, 2001). Major uplift occurred in late Paleocene to middle Eocene time (Bryant and Nichols, 1988). The Uinta uplift projects westward into the Cottonwood arch, in the central Wasatch Range, which exposes in part correlative Late Proterozoic rocks that were uplifted principally in the Neogene. These uplifts divide the Sevier orogenic belt into two segments marked by abrupt changes in stratigraphy within allochthons and by differences in the age and amount of thrust displacement (see, for example, Bradley and Bruhn, 1988).

The Center Creek quadrangle lies on the southern side of this uplift, and also straddles the Charleston thrust fault, which bounds the northeastern edge of the Charleston-Nebo salient of the Sevier orogenic belt. The northern part of this salient (the Charleston allochthon) was emplaced during the late Early Cretaceous and early Late Cretaceous at the height of the Sevier orogeny in central Utah (Bryant and Nichols, 1988). Constenius (1996) described the extensional collapse of the Sevier orogenic belt during a late Eocene to early Miocene episode of crustal extension. Half grabens superimposed on the Charleston-Nebo salient show that 3 to 4 miles (5-7 km) of extension occurred on the sole thrust during the late Eocene to early Miocene (Royse, 1983; Reiss, 1985; Houghton, 1986; Constenius, 1995, 1996).

The Charleston-Nebo salient is bounded on the east by the Strawberry thrust and on the south by the Nebo thrust. The Charleston and Strawberry thrusts are structurally linked beneath a cover of syn- and postorogenic strata and were emplaced in the early Late Cretaceous, with the last major movement immediately southwest of the Uinta Mountains in the Campanian (Bryant and Nichols, 1988). The Nebo thrust is a separate splay that was emplaced earlier (Bryant and Nichols, 1988). Estimates of eastward-directed displacement of the Charleston allochthon range up to about 40 miles (65 km) (Crittenden, 1961), but cutoff relations between hanging-wall and footwall strata of the Thaynes Formation suggest a displacement of about 19 miles (30 km) (Gallagher, 1985). Subsequent magmatism and Basin and Range extension overprinted much of this earlier phase of extension (Constenius, 1996).

Charleston Thrust Fault

The Charleston thrust fault bounds the northeast flank of the Charleston-Nebo salient (Baker, 1976; Bryant, 1992), but is nowhere well exposed in the Center Creek quadrangle. We believe the fault trends southeast up the Center Creek drainage where it places the Pennsylvanian Wallsburg Ridge Member of the Oquirrh Formation over southwest-dipping early Late Cretaceous strata. In the Center Creek quadrangle, emplacement of the Charleston allochthon can only be dated as post-early Turonian (early Late Cretaceous), but exposures to the east along the correlative Strawberry thrust show an emplacement age of Turonian to Campanian (middle Late Cretaceous) (Bryant and Nichols, 1988); in the Co-op Creek quadrangle, Coogan and Constenius (2000) mapped allochthonous strata thrust over the Upper Cretaceous Mesaverde Formation. Recent thermochronology data (Kurt Constenius, written communication, March 8, 2001) suggest that the thrust sheet was emplaced between about 90 and 40 million years ago (early Late Cretaceous to late Eocene).

Southeast of Crooked Creek, the Charleston thrust fault is wholly concealed by morainal deposits in the Center Creek drainage, whereas to the northwest, the fault is mostly concealed by a variety of alluvial, colluvial, and mass-movement deposits. The Charleston thrust is exposed, however, in a small road cut in the SW1/4SE1/4SW1/4 section 19, T. 4 S., R. 6 E. There, brecciated Wallsburg Ridge orthoquartzite is juxtaposed against multi-hued mudstone and siltstone of likely early Late Cretaceous age. To the northwest, the thrust fault is concealed by tuffaceous deposits of the lower Keetley Volcanics.

Our mapped trace of the Charleston thrust differs from that of previous workers. Baker (1976) inferred that the thrust is buried under Keetley strata about 1 to 2 miles (1.5-3 km) north of where we now know it to be, probably because he did not recognize Cretaceous strata in the Center Creek drainage. Bryant (1992) mapped Cretaceous beds in the upper reaches of the Center Creek drainage, and so correctly placed the thrust there, but he missed correlative beds along strike to the northwest; thus, he too showed the thrust under Keetley strata nearer to the mouth of Center Creek. Our mapping shows that the Charleston thrust places the Pennsylvanian Wallsburg Ridge Member over early Late Cretaceous strata along its entire length in the middle and upper reaches of the Center Creek drainage; it is concealed under Keetley Volcanics at the mouth of the Center Creek drainage. Outcrop patterns of Mesozoic strata in the northwestern corner of the Center Creek quadrangle suggest that the thrust may cut down-section to the northwest, perhaps placing Wallsburg Ridge strata over Late Jurassic or Early Cretaceous strata under the eastern portion of Heber Valley. Such a trend indicates that the Charleston thrust ramps up-section from west to east and from south to north. Thus, we interpret the thrust as a sidewall decollement ramp in this area. The position of the Charleston thrust is also constrained by a seismic line that crosses part of the Center Creek quadrangle between the mouths of Daniels Canyon and Center Creek canyon.

The Charleston thrust separates Mississippian strata from a nearly complete section of the Jurassic Twin Creek Limestone in the Placid Oil Company West Daniels Land #1 well (T. 5 S., R. 5 E., section 11). Our interpretations of the West Daniels Land #1 well differ somewhat from those of Sprinkel (1994), who reported that the Charleston thrust places the Manning Canyon Shale (Mississippian) over the Arapien Shale (Jurassic) at a depth of 10,920 feet (3,329 m). We believe that the interval enclosing the Charleston thrust is more complex. Geophysical logs and rock cuttings from the West Daniels Land #1 well show a 110-foot-thick (34 m) interval of very pale-orange orthoquartzite at a depth of 11,420 to 11,530 feet (3,482-3,515 m) that we believe to be the Tintic Quartzite (Cambrian) caught between splays of the Charleston thrust fault. Such a relationship is present to the west at Deer Creek Reservoir about 7 miles (11 km) west of the well (Baker, 1976), and in the Aspen Grove quadrangle (Baker, 1964). In the West Daniels Land #1 well, the Charleston thrust thus places Mississippian strata over a sliver of the Tintic Quartzite over a nearly complete section of the Twin Creek Limestone. The Tintic is likely a thrust horse carried in the hanging wall of the thrust sheet.

Interpretation of beds immediately above the Tintic Quartzite remains equivocal. Well logs and cuttings reveal about 800 feet (245 m) of highly brecciated, very fine-grained limestone and shale. Doug Sprinkel (Utah Geological Survey, verbal communication, November 8, 1999) reported difficulties in drilling this interval, where shales apparently flowed into and repeatedly bridged the hole. The American Stratigraphic Company log for the hole shows a 15-foot-thick (5 m) bed of anhydrite at a depth of about 11,010 feet (3,357 m), near the middle of this brecciated interval; geophysical logs suggest that the bed is impure, and we found no anhydrite in the well cuttings. Unpublished palynomorph data from this well show a low-diversity spore assemblage of abundant *Lycospora* spp. and rare *Punctatisporites* spp. and *Denososporites* spp. that suggest a Mississippian(?) to earliest Pennsylvanian age for at least the upper part of this brecciated interval. The lower half of the brecciated interval yielded little palynological data. Sprinkel (1994) thus reasonably interpreted this interval as the Manning Canyon Shale over the Arapien Shale. Co-author Welsh, however, believes that this interval is intensely fractured Bridal Veil Limestone Member of the Oquirrh Formation, not the Manning Canyon Shale, but admits uncertainty about the apparent anhydrite, which is unknown in either Pennsylvanian or Mississippian strata of the Oquirrh basin. While the identification of strata in this interval remains uncertain, inferred duplexes in Mississippian strata under the flanks of the Big Hollow syncline (see cross section A-A′) also suggest the presence of Manning Canyon strata in the well. Cross section A-A′ thus shows the upper part of the Manning Canyon Shale underlain by a normal fault that at this depth is substantially parallel to bedding. The anhydrite and enclosing strata may represent a thrust splay in Jurassic strata. This normal fault, and backsliding on the Charleston thrust discussed later, probably occurred following gravitational collapse of the Sevier orogenic belt during late Eocene to early Miocene crustal extension (Constenius, 1996).

Allochthonous Rocks

Allochthonous rocks of the Charleston thrust plate, located in the southern portion of the quadrangle, are folded into the paired Daniels Canyon anticline and Big Hollow syncline. The Daniels Canyon anticline, first mapped in a general way by Baker (1976), is best defined by outcrops of the Shingle Mill Limestone. The anticline plunges southeast, and at the mouth of the canyon, the axis of the fold lies just north of State Highway 40. To the southeast, bedding attitudes show the axis climbs up to the crest of Hogsback Ridge in the vicinity of Mud Spring. The anticline appears to die out farther southeast. The crest of the anticline is broken by two steeply dipping normal faults that trend parallel to the axis of the fold and create a horst along the anticlinal axis. The southwestern fault has a displacement of about 1,200 feet (370 m) and the northeastern fault a displacement of about 900 feet (275 m) near cross section A-A′. The Big Hollow syncline, named by Welsh (unpublished notes, 1980-81) for exposures at Big Hollow in the adjacent Charleston quadrangle, is best defined by outcrops of the lower unit of the Granger Mountain Member of the Oquirrh Formation. The syncline plunges gently southeast, roughly parallel to the Daniels Canyon anticline. These fold axes trend parallel to the Charleston thrust fault, as might be expected here if the Charleston thrust is a sidewall decollement ramp.

In the southeast portion of the quadrangle, the Charleston allochthon is cut by several north- to northwest-trending, mostly down-to-the-west normal faults. The faults are identified principally by down-dropped blocks of Keetley Volcanics that are preserved in a small graben and a few half grabens. The displacement on the largest of these faults is about 1,000 feet (300 m) or perhaps slightly more. This fault system is believed to be linked with an inferred down-to-the-west normal fault that trends through the lower reaches of the

Center Creek drainage. Along Center Creek, the quartzite-boulder unit of the Keetley Volcanics is about 800 feet (250 m) lower in elevation on the west side of Center Creek than it is east of this drainage. In the Center Creek quadrangle, there is no evidence of post-Keetley relaxation along the trace of the Charleston thrust itself.

Smaller structures may be present in the thrust sheet where exposures are poor. In the southeastern corner of the quadrangle, dip reversals in Wallsburg Ridge strata suggest the presence of additional faults or folds, but poor exposures and lack of marker beds preclude mapping such structures. In the middle reaches of Boomer Canyon, upper Wallsburg Ridge and lower Wolfcampian limestone strata show a marked change in the strike of beds. East of Boomer Canyon beds strike northeast, whereas to the west they strike northwest. Although exposures are limited, no faults were identified in this area. These anomalous dips may reflect a subsidiary, oblique fold on the nose of the Daniels Canyon anticline.

Parautochthonous Rocks

In the Center Creek quadrangle, exposed para-autochthonous rocks include the Nugget Sandstone, Twin Creek Limestone, and the lower Frontier Formation. These beds dip uniformly southwest towards the Charleston thrust and are mostly concealed by the Keetley Volcanics and Quaternary deposits. Their homoclinal dip and parautochthonous nature reflects the quadrangle's location at the southwestern margin of the Uinta uplift (Constenius and Stern, 1998). Bryant and Nichols (1988) reported that the first upward movement of this part of the Uinta uplift probably occurred in the late Campanian to early Maastrichtian (latest Cretaceous), but that the major contractional movement occurred in the late Paleocene and middle Eocene. Because the latest Eocene to Oligocene Keetley Volcanics rest subhorizontally over these parautochthonous strata in the Center Creek quadrangle, most movement of the Uinta uplift in this immediate area must be pre-latest Eocene in age. Presumably, this uplift tilted the Charleston thrust fault as well, which was already steeply dipping in this area as a result of its inferred position as part of a sidewall ramp.

A small, down-to-the-northeast normal fault offsets the Nugget/Twin Creek contact in the NW1/4 section 8, T. 4 S., R. 6 E. Displacement on this fault is less than a few tens of feet. About 1 mile (1.6 km) to the southeast, a marker bed in the Keetley Volcanics shows a similar displacement. These two breaks may reflect displacement along the same fault. We infer a second down-to-the-northeast normal fault, with a displacement of at least 100 feet (30 m), immediately to the west to account for apparent offset of the Nugget/Twin Creek contact and the absence of the tuffaceous unit of the Keetley Volcanics east of this inferred fault. Faults with significant left-lateral displacement may also explain mapped relationships.

The quartzite-boulder unit of the Keetley Volcanics gradually decreases in elevation toward the north, but it also appears to drop abruptly across two west-trending drainages. One of these drainages straddles the common boundary of sections 18 and 19, T. 4 S., R. 6 E., across which the quartzite-boulder unit is dropped down about 400 feet (120 m) to the north. The unit is also dropped down about 200 feet (60 m) across the northwest-trending drainage that passes through the NE1/4 section 18, T. 4 S., R. 6 E. That the quartzite-boulder unit appears to be stepped down to the north suggests the presence of a pair of unrecognized faults, possible paleotopographic influences, or structures associated with a possible northwestward continuation of inferred sackungen along the crest of the ridge between the Lake Creek and Center Creek drainages.

Heber Valley and Round Valley

Heber and Round Valleys are two of the southernmost back valleys (fault-bounded valleys east of the Wasatch fault zone) first described in some detail by Gilbert (1928). In plan view, Heber Valley resembles an irregular triangle that is 8 to 10 miles (13-16 km) long on a side; only the eastern part of the valley lies within the Center Creek quadrangle. The valley is somewhat anomalous in that its margins are sinuous and lack evidence of late Quaternary, basin-bounding faults (Bromfield and others, 1970; Sullivan and others, 1988; Bryant, 1992). Sullivan and Nelson (1983) trenched across a 2,000-foot-long (600 m), 3- to 39-foot-high (1-12 m) linear scarp at the entrance to Big Hollow on the south side of the valley in the Charleston quadrangle and concluded that it formed as an erosional feature. Similar escarpments are cut in level 2 alluvial-fan deposits both west and east of the mouth of the Center Creek drainage (in the central parts of sections 11 and 15), and, although they have not been trenched, we believe that these too are erosional in nature. Sullivan and Nelson (1983) also suggested that bedrock facets between embayments along the south margin of Heber Valley may have formed by lateral stream migration and erosion of brecciated Oquirrh bedrock by the Provo River and its tributaries.

However, inferred Heber Valley bounding faults (Bryant, 1992) seem to be required to explain: (1) the depth of Heber Valley, which may have up to 790 feet (240 m) of basin fill (Peterson, 1970), (2) the depth of Daniels Canyon, and (3) the capture of the Keetley drainage by the Provo River in Heber Valley (Sullivan and others, 1988). Baker (1964, 1976) showed that the structural floor of Heber Valley lies at a lower elevation than its outlet, requiring that the valley be down-dropped relative to its outlet along unmapped faults. Sullivan and others (1988) summarized evidence that suggests Heber Valley may have been near its present relative level for the last several hundred thousand years even though the lower and probably the upper Provo Canyons have deepened considerably over the same time period. They suggested that a combination of mid-Tertiary extension and episodes of erosion and aggradation by the Provo River and its tributaries best explains the present topography of Heber Valley. The degree to which Basin and Range extension has overprinted earlier extensional structures of the valley is uncertain.

In contrast, Quaternary basin-bounding faults are easily recognized at Round Valley (Sullivan and others, 1988; Bryant, 1992). Round Valley is entirely within the Charleston allochthon, and the lack of mid-Cenozoic deposits there suggests that the valley developed after mid-Cenozoic reactivation of the Charleston thrust (Sullivan and others, 1988). The easternmost Round Valley fault cuts older alluvial-fan deposits in the extreme southwest corner of the Center Creek quadrangle. The resultant scarp is degraded and varies from about 50 to 80 feet (15-24 m) high. While the age of the most recent displacement on the Round Valley faults is not constrained, Hecker (1993) suggested that it is middle to late Pleistocene, based in part on comparison with the better studied Morgan fault (40 miles [65 km] to the north).

ECONOMIC GEOLOGY

Aggregate

In the past, aggregate was extracted from a variety of alluvial and colluvial deposits in the Center Creek quadrangle. The Materials Inventory of Wasatch County (Utah State Department of Highways, 1966) contains basic analytical information on these inactive or abandoned workings, which are shown on the map. Alluvial deposits in the quadrangle at the eastern end of Heber Valley contain large amounts of moderately sorted sand and gravel.

Crushed stone is presently quarried from highly fractured orthoquartzite in the Bear Canyon Member of the Oquirrh Formation at the mouth of Daniels Canyon, and a similar quarry in the Wallsburg Ridge Member near the canyon mouth of Center Creek closed in the late 1990s. These quarries tap a nearly unlimited supply of highly fractured and brecciated Oquirrh sandstones. Because these sandstones are siliceous and generally only slightly feldspathic, they are classified as orthoquartzite. When crushed and screened, they provide a high-quality source of aggregate.

Organic shales from the Frontier Formation are mined on the west side of Rockport Reservoir, about 20 miles (32 km) north of the Center Creek quadrangle, and are thermally expanded into “bloated shale,” a lightweight aggregate useful for a variety of applications. Thin organic shales and organic silty sandstone were observed in the upper reaches of the Center Creek drainage, as described in the stratigraphy section of this report. However, exposures there are poor and the extent of these beds is unknown.

Oil and Natural Gas

Exploration for oil and gas in the Center Creek quadrangle resulted in the drilling of the Placid Oil Company West Daniels Land #1 wildcat well (API # 43-051-30014), which was spudded in 1982 and plugged and abandoned in 1983, in the NE1/4NW1/4NW1/4 section 11, T. 5 S., R. 5 E. The well is one of many drilled during the overthrust exploration boom of the late 1970s and early 1980s. The well was abandoned at a depth of 17,322 feet (5,281 m) in the Weber Quartzite before reaching the intended target, a structure in Mississippian carbonates below the Charleston thrust, due to repeated problems believed to result from shales flowing into and bridging the hole at a depth of about 10,800 feet (3,290 m) (Doug Sprinkel, Utah Geological Survey, verbal communication, November 4, 1999). Oil shows were reported but not tested in Park City and Weber strata. A well drilled in 1950 near the mouth of Daniels Canyon, in the SW1/4NE1/4NE1/4 section 21, T. 4 S., R. 5 E., just west of the Center Creek quadrangle, was reported to have reached a depth of only 515 feet (157 m) (Hansen and Scoville, 1955). No other information is available for this well.

Ritzma (1975) described the Daniels Canyon oil-impregnated rock deposit (Chinese Wax mine) near Highway 40, about 4.5 miles (7 km) south of the Center Creek quadrangle. The mine was worked sporadically for 60 years or more beginning around 1900. The mine exploited a small deposit of black, viscous, waxy oil emplaced in brecciated Oquirrh (Freeman Mountain sandstone facies of the Granger Mountain Member) strata. The oil probably migrated laterally into the brecciated zone from oil shale in onlapping Tertiary Green River Formation (Doug Sprinkel, written communication, 1999). No similar oil-impregnated rocks were observed in the Center Creek quadrangle.

Prospects

Despite the fact that correlative Oquirrh strata are in part host to the mineral deposits of the Bingham mining district 40 miles (65 km) to the west, and despite the proximity of the nearby Park City mining district, we observed no evidence of mineralization in Oquirrh Formation or other bedrock strata in the Center Creek quadrangle. No prospects were identified in the field or in Utah Geological Survey files.

Geothermal Resources

The geothermal potential of the Center Creek quadrangle is unstudied and unknown, but thermal springs are present near Midway, on the west side of Heber Valley. The Midway springs issue from several widespread, coalescing travertine and tufa mounds with water temperatures that range from 100 to 114 degrees Fahrenheit (38-46°C) (Baker, 1968; Kohler, 1979; Blackett, 1994). Springs at the Mountain Spa and Homestead Resorts are used to heat swimming pools and for therapeutic baths. Baker (1968) concluded that the water is meteoric, originating in the mountains to the northwest and emerging through fractures at Midway. The heat source is uncertain, but is attributed to deep circulation (Baker, 1968; Mayo and Loucks, 1995).

Building and Ornamental Stone

The Nugget Sandstone has long been quarried in northern Utah as a source of building and ornamental stone. Quarries near the mouth of Lake Creek, at the east end of Heber Valley, still provide a reddish-orange, or “salmon” colored, fine- to medium-grained sandstone widely used in Utah for building and decorative work. The sandstone naturally splits into thin sheets and blocks along cross-bedding surfaces and closely spaced joints. This sandstone was used for a number of historic buildings in Heber City.

WATER RESOURCES

Average annual precipitation in the Center Creek quadrangle is between about 20 and 30 inches (50-75 cm) (Baker, 1970). Most of this precipitation is associated with low-pressure storms between October and May, although significant precipitation also occurs in August during cloudburst storms.

About half of the annual precipitation falls as snow in Heber Valley, whereas more than half falls as snow in the higher elevations (Richardson, 1976). Runoff and spring flow are concentrated in several perennial and numerous ephemeral stream channels within the quadrangle.

The surface- and ground-water resources in the Center Creek quadrangle have been evaluated as part of regional hydrogeologic studies in the area (Baker, 1970; Roark and others, 1991) and for classification of the Heber Valley valley-fill aquifer (Jensen, 1995; Lowe, 1995). The following information is largely compiled from these sources.

Lake Creek, Center Creek, and Daniels Creek flow across the quadrangle from southeast to northwest and are relatively major tributaries to the Provo River, located west of the quadrangle. Although perennial, the streams are diverted at the valley margins for irrigation and flow within Heber Valley only during winter and early spring. Daniels Creek is the largest of the three streams, having an estimated discharge of 15.6 cubic feet per second (0.44 m^3/s) (Hyatt and others, 1969). Estimated average discharges of Lake and Center Creeks are 10.9 cubic feet per second (0.31 m^3/s) and 6.5 cubic feet per second (0.18 m^3/s), respectively (Hyatt and others, 1969). Surface water in the eastern Heber Valley area is calcium-bicarbonate type and is generally low in dissolved solids.

Ground water occurs in fractured bedrock and in the valley-fill aquifer of Heber Valley. The primary source of public-water supplies for the community of Center Creek is spring water that discharges from bedrock. Jurassic sandstone and limestone yield calcium-magnesium-bicarbonate-type water having total-dissolved-solids (TDS) concentrations of less than 500 mg/L, and Tertiary volcanic rocks yield calcium-bicarbonate-type water having TDS concentrations of less than about 1,000 mg/L (Baker, 1970). Most water wells in the area draw from unconsolidated valley-fill sediments. The valley-fill deposits of eastern Heber Valley form a single, essentially homogeneous, unconfined aquifer. Ground water is as shallow as 5 to 20 feet (1.5-6 m) below the ground surface at the eastern end of Heber Valley, and becomes deeper to the west. The valley-fill aquifer yields calcium-bicarbonate-type water having TDS concentrations of less than 500 mg/L (Baker, 1970).

GEOLOGIC HAZARDS

Geologic hazards are naturally occurring geologic processes that may present a danger to life and property, and are important factors to be considered prior to development. Hazards that exist in the Center Creek quadrangle include landsliding, stream flooding, alluvial-fan flooding, debris flows, shallow ground water, problem soil and rock, earthquakes, and radon. Hylland and others (1995) mapped geologic-hazard areas in western Wasatch County, including much of the Center Creek quadrangle, and discussed considerations for development in these areas.

Landslides

Several types of landslides exist within the Center Creek quadrangle, including shallow debris slides, deep-seated earth or rock slumps, and earth flows. The landslides are typically in Pleistocene glacial deposits, the Tertiary Keetley Volcanics, the Frontier Formation, and in colluvial and residual deposits derived from these units. Many of the landslides are prehistoric, but historical landslides are abundant in the Lake Creek and Center Creek drainages. Although dormant or inactive, prehistoric landslides pose a hazard in that they may become reactivated as the result of changes in ground-water conditions, seismic activity, or slope modifications resulting from erosion or development. An example of reactivation of a prehistoric landslide is provided by the Pine Ridge landslide in the NE1/4 section 9, T. 4 S., R. 6 E. (Ashland and Hylland, 1997). This deep-seated slump in Pleistocene glacial deposits underlies about 114 lots in the Timber Lakes Estates subdivision. An 11-acre (4.4 ha) section of the landslide reactivated sometime during the winter or early spring of 1985-86, resulting in damage to a cabin and formation of a main scarp up to 15 feet (5 m) high that crosses several vacant lots. Results of a preliminary geotechnical-engineering slope-stability study indicate the northern part of the Pine Ridge landslide, adjacent to the incised Lake Creek channel, may be marginally stable under static conditions, and that movement of the entire landslide could result from strong earthquake ground shaking at a time of high ground-water levels (Ashland and Hylland, 1997). Critical slope inclinations, which represent slope inclinations above which landsliding has typically taken place under climatic conditions similar to the present, have been calculated by Hylland and Lowe (1997) for landslides in the Pleistocene glacial deposits and some of the bedrock units present in the quadrangle.

Two other types of mass movement may also be a hazard in the Center Creek quadrangle. The first type, rock fall, generally has not been a significant hazard because of a lack of source areas near residential areas. However, rock falls may occur locally below steep exposures such as road cuts, cliffs, or stream banks, and may be especially numerous during strong ground shaking accompanying earthquakes. Because of steep slopes adjacent to many areas along Highway 40, the rock-fall hazard is probably greatest in Daniels Canyon. The second type of mass movement is a class of ridge-top deformation features called “sackungen,” which are thought to result from large-scale, deep-seated gravitational spreading. Features ascribed to sackungen elsewhere in the United States and Europe (see, for example, Varnes and others, 1989; McCalpin and Irvine, 1995) are present on the divide between the Lake Creek and Center Creek drainages, in the S1/2 section 16 and N1/2 section 21, T. 4 S., R. 6 E., and include ridge-top troughs or grabens and uphill-facing scarps. Detailed study is needed to determine the origin of the suspected sackungen features in the Center Creek quadrangle, and to evaluate their associated hazard.

Stream Flooding

Stream flooding is typically associated with rapid spring snowmelt in the mountains and summer cloudburst rainstorms. Stream flooding can be a hazard in areas delineated by the Federal Insurance Administration (FIA) and the Federal Emergency Management Agency (FEMA) as 100-year flood plains as well as in minor drainages not delineated by the FIA or FEMA. Flood-hazard areas in minor drainages are shown in Hylland and others (1995) and generally correspond to areas of Holocene alluvium (Qal_1). In addition to flooding associated with natural alluvial processes, flooding may also result from the failure of a dam. There are nine small dams in the Lake Creek and Center Creek drainages that are considered high-hazard dams (Matthew Lindon, Utah Division of Water Rights, Dam Safety Section, written communication, 1996); the high hazard rating is based on dam size, reservoir volume, and the possibility of loss of life in the event of a dam failure (Lindon, 1992).

Alluvial-Fan Flooding and Debris Flows

Alluvial-fan flooding, characterized by little advance warning and unpredictable flow paths, is a hazard on Holocene alluvial fans (Qaf_1). The flooding typically occurs as a debris (hyperconcentrated) flood, which is a mixture of soil, organic material, and rock debris transported by fast-moving floodwaters (Wieczorek and others, 1983). Holocene alluvial fans can also be affected by debris flows, which occur when sediment and debris in the floodwaters create a muddy slurry much like wet concrete. Normal stream flow, debris floods, and debris flows form a continuum of sediment/water mixtures that grade into each other with changes in the relative proportion of sediment to water and with changes in stream gradient (Pierson and Costa, 1987). Debris floods contain 40 to 70 percent solids by weight, and debris flows contain 70 to 90 percent solids by weight (Costa, 1984). Debris floods and debris flows can be hazards in the stream channels above alluvial fans as well as on the fans themselves. Like normal stream flooding, debris floods and debris flows can result from intense precipitation during cloudburst rainstorms and rapid spring snowmelt. Debris flows can also mobilize directly from landslides.

Alluvial-fan flooding and debris flows generally have not been significant hazards in the Center Creek quadrangle in historical time, but new development is expanding to and beyond the valley margins where alluvial fans are common. A potential hazard exists on Holocene alluvial fans and in stream channels, especially if the vegetation in drainage basins is damaged by wildfire, grazing, or development.

Shallow Ground Water

Ground water is considered shallow when the water table is within 30 feet (9 m) of the ground surface (Hecker and others, 1988). In areas of unconsolidated surficial deposits, which is where most construction takes place, shallow ground water can present a flooding hazard to below-grade structures, especially if the ground water is within about 10 feet (3 m) of the ground surface. Other hazards associated with shallow ground water include inundation of landfills and waste dumps, flooding of wastewater-disposal systems, and ground-water contamination. Shallow ground water is present in Heber Valley, in the vicinity of the mouths of the Lake Creek and Center Creek drainages, and in localized areas in the upper Lake Creek and Center Creek drainages (Baker, 1970; Woodward and others, 1976; Hecker and others, 1988; Hylland and others, 1995). Because the tuffaceous unit of the Keetley Volcanics, and overlying residual and colluvial debris, appears to be poorly drained, shallow ground water may be locally present in these units.

Problem Soil and Rock

Problem soils are surficial-geologic materials susceptible to volumetric change, collapse, subsidence, or dissolution that can cause engineering problems. Problem soils that may exist in the Center Creek quadrangle include collapsible soils, expansive soils, and organic soils.

Collapsible soils are loose, dry, low-density deposits that are susceptible to hydrocompaction, a phenomenon that causes a volume reduction or collapse when the soil is saturated for the first time following deposition (Costa and Baker, 1981). In Utah, collapsible soils are typically associated with alluvial-fan deposits (Mulvey, 1992), but some fine-grained colluvial or alluvial deposits may also have collapsible soils (Owens and Rollins, 1990). Collapsible soils are most likely to be found in areas underlain by Holocene alluvial fans containing clayey deposits.

Expansive soils are clay-rich, and can shrink and swell with changes in moisture content. When water is added to certain varieties of clay minerals (smectite, in particular), the clay may swell by absorption of water between clay particles or into the crystal lattices that make up the individual particles (Tourtelot, 1974; Mulvey, 1992), causing the clay-bearing soil to expand. As the soil dries, the loss of water causes it to shrink. U.S. Soil Conservation Service maps indicate that soils having a moderate to high shrink-swell potential are present in the Lake Creek and Center Creek drainages (Woodward and others, 1976). Desiccation cracks in soils developed on clay-rich Cretaceous strata and Tertiary Keetley Volcanics show that these rocks exhibit a slight shrink-swell potential. Such soils may also be more susceptible to piping and gullying than other soils in the quadrangle.

Organic soils contain peat, which consists of accumulations of incompletely decomposed and disintegrated plant material. Peat is characterized by high void ratios and moisture contents, and therefore is susceptible to extreme reductions in volume that may include shrinkage, settlement, and compression (Bell, 1983). Post-glacial alluvial mud deposits (Qam) in the Center Creek quadrangle contain organic matter and could be subject to varying degrees of volume reduction.

Earthquake Hazards

The Center Creek quadrangle lies within the Intermountain seismic belt (Smith and Sbar, 1974; Smith and Arabasz, 1991), a generally north-south-trending zone of earthquake activity that bisects Utah. Many faults within this zone are active and capable of producing earthquakes, including the Wasatch fault, located about 20 miles (32 km) west of the quadrangle. Surface-faulting earthquakes on the Wasatch fault or other potentially active faults in the area could be of magnitude 6.5 or larger. In addition, smaller earthquakes that do not cause surface fault rupture (up to magnitude 6.5), and thus are not necessarily attributable to a mapped fault, could also cause damage and may occur anywhere in the area (Smith and Arabasz, 1991). Earthquake hazards in the quadrangle include ground shaking, surface-fault rupture, and landsliding.

Small to moderate earthquakes are not uncommon in western Wasatch County. A magnitude 4.7 earthquake with an epicenter about 3 miles (5 km) east of Heber City occurred on October 1, 1972, and caused minor damage associated with ground shaking in Heber City and the nearby communities of Midway and Wallsburg (Langer and others, 1979). Also, ground shaking from an earthquake on February 13, 1958, caused minor damage in Wallsburg, just west of the Center Creek quadrangle in Round Valley (Brazee and Cloud, 1960). Based on a maximum Modified Mercalli intensity of VI, this earthquake had a magnitude of about 5.0 (Arabasz and McKee, 1979; Hopper, 1988).

Earthquake ground motions are typically reported in units of acceleration as a fraction of the force (acceleration) of gravity (*g*). In general, the greater the acceleration or "*g*" force, the stronger the ground shaking and the more damaging the earthquake. National seismic-hazard maps developed by Frankel and others (1996; also U.S. Geological Survey, 1999) give probabilistic ground motions in terms of peak ground acceleration and 0.2-, 0.3-, and 1.0-second-period spectral accelerations having 10, 5, and 2 percent probabilities of exceedance in 50 years. Probabilistic ground-motion values applicable to bedrock sites in the middle of the Center Creek quadrangle are summarized in table 1.

Table 1. *Probabilistic ground-motion values (in g) generally applicable to rock sites in the middle of the Center Creek quadrangle, Wasatch County, Utah. Data from U.S. Geological Survey (1999).*

	10% PE in 50 yr	**5% PE in 50 yr**	**2% PE in 50 yr**
PGA	0.15	0.21	0.32
0.2 sec SA	0.34	0.48	0.74
0.3 sec SA	0.30	0.42	0.63
1.0 sec SA	0.11	0.16	0.25

Abbreviations: *PE, probability of exceedance; PGA, peak ground acceleration; SA, spectral acceleration. Ground-motion values determined from national seismic-hazard maps (Frankel and others, 1996) using latitude/longitude computations available online at geohazards.cr.usgs.gov/eq/index.html, and represent general values for ground shaking on rock (International Building Code site class B) at latitude 40°26′1″N., longitude 111°18′45″W. Ground motions at any specific site will vary from these values because of site-specific rock and soil conditions.*

In some cases, earthquake ground motions can be amplified and shaking duration prolonged by local site conditions. Soft clayey soils and deep sediment-filled basins, as well as thin gravelly soils over shallow bedrock, can amplify ground motions above the levels found in nearby bedrock. The amount of amplification varies with the frequency of the seismic waves. Recent theoretical studies have shown that shallow, "stiff" soils (for example, sand or gravel deposits present locally in Heber Valley) may amplify the higher frequency seismic waves that are most damaging to low-rise buildings (Adan and Rollins, 1993). Design and construction of new buildings in the Center Creek quadrangle should follow the seismic provisions in the *International Building Code* (International Code Council, 2000), including use of appropriate ground-motion values.

A surface-fault-rupture hazard is associated with the fault that cuts older alluvial-fan deposits (Qafo) in the extreme southwest corner of the quadrangle (plate 1). This fault is one of three normal faults bounding and within Round Valley, which lies mostly west of the Center Creek quadrangle. Ages and recurrence intervals of movement on the Round Valley faults are unknown and detailed studies are needed. Sullivan and others (1988) speculated that the Round Valley faults may have been active in late Quaternary time, and Hecker (1993) estimated an earthquake surface-wave magnitude of M_S 6.5-6.75 associated with movement on one of these faults. Hylland and others (1995) show surface-fault-rupture special-study zones associated with the Round Valley faults and provide recommendations for hazard studies prior to development within these zones. Poorly understood Heber Valley bounding faults may also present a surface-fault-rupture hazard.

Landslides and rock falls are hazards likely to occur on steep slopes during an earthquake. Depending on prevailing ground-water and slope conditions and the severity of shaking, new landslides may form and pre-existing landslides may reactivate. Rock falls may be especially numerous beneath cliffs and road cuts that expose poorly consolidated bouldery deposits, or where boulders, such as glacial erratics, lie on sloping ground surfaces.

Indoor Radon

Radon (^{222}Rn) is an odorless, tasteless, and colorless radioactive gas that forms as a product of radioactive decay. Although outdoor radon concentrations do not reach dangerous levels because air movement dissipates the gas, people can be subject to a radon hazard in buildings that have poor circulation. Health officials believe breathing elevated levels of radon over time increases a person's risk of lung cancer (National Council on Radiation Protection and Measurements, 1984; Samet, 1989).

Although radon is present in small concentrations in nearly all rocks and soils, several geologic factors control the radon hazard. The primary factor is the distribution of uranium-enriched rock and soil. Granite, some metamorphic and volcanic rocks, and black, organic- or phosphate-rich sedimentary rocks are generally associated with indoor-radon hazards. Once uranium is present in rock or soil, other factors enhance or impede radon production and movement, including permeability and water saturation (Tanner, 1964, 1980; Barretto, 1975). High permeability enhances radon movement by allowing the gas to diffuse through the rock or soil. Water saturation inhibits radon movement by filling pore spaces and restricting the flow of soil gas (Tanner, 1980).

Although indoor radon generally is not a major geologic hazard in the Center Creek quadrangle, combinations of geologic factors contributing to a potential hazard exist locally, particularly in areas underlain by the Keetley Volcanics. As part of a statewide study of geologic conditions related to radon hazard, Black (1993) identified a moderate radon-hazard potential in all of the Center Creek quadrangle area except for Heber Valley, where the hazard potential is low due to shallow ground water. Indoor testing is the only reliable way to determine if a radon hazard exists (U.S. Environmental Protection Agency, 1992).

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APPENDIX

Spores, pollen, and microplankton analyses by Gerald Waanders, Consulting Palynologist

Sample number CC7899-1

Spores and pollen:

Araucariacites australis	(A)
Classopolis classoides	(A)
Deltoidopora spp.	(R)
Exesipollenites tumulus	(R)
Liliacidites peroreticulatus	(R)
Parvisaccites radiatus	(R)
Rugubivesiculites reductus	(R)
Taxodiaceae	(F)
Tricolporopollenites granulocuneus	(R)
Undifferentiated Bisaccates	(A)

Microplankton:

Aptea polymorpha	(R)
Canninginopsis colliveri	(R)
Florentinia cooksoniae	(R)
Microforminifera linings	(R)
Spiniferites ramosus	(R)

Organic recovery: 20% amorphous, 30% cuticular, and 50% woody
Age: middle to late Cenomanian
Environment: Nearshore marine, lagoonal, or estuarine

R = rare, < 6 specimens per slide; F = frequent, 6 to 15 specimens per slide; C = common, 16 to 30 specimens per slide; A = abundant, > 30 specimens per slide.

Sample number CC7899-2

Spores and pollen:

Araucariacites australis	(R)
Cicatricosisporites australiensis	(R)
Cicatricosisporites brevvilaesuratus	(R)
Classopolis classoides	(A)
Deltoidopora spp.	(R)
Exesipollenites tumulus	(R)
Gleicheniidites senonicus	(F)
Leptolepidites tenuis	(R)
Liliacidites peroreticulatus	(F)
Parvisaccites radiatus	(R)
Rugubivesiculites reductus	(R)
Taxodiaceae	(F)
Tricolpites sp. A Nichols & Jacobson	(R)
Undifferentiated *Bisaccates*	(R)

Microplankton:

Canninginopsis colliveri	(R)
Circulodinium distinctum	(R)

Organic recovery: 5% amorphous, 15% cuticular, and 70% woody
Age: middle to late Cenomanian
Environment: Nearshore marine, beach, or deltaic

R = rare, < 6 specimens per slide; F = frequent, 6 to 15 specimens per slide; C = common, 16 to 30 specimens per slide; A = abundant, > 30 specimens per slide.

Molluscan taxa identified by James I. Kirkland, State Paleontologist, Utah Geological Survey, August 1999
Molluscan taxa from sample locations CC7899-1 and CC7899-2:

BIVALVIA

Barbatia micronema (Meek, 1873)	B
Brachiodonte multilinigere (Meek, 1873)	B
Phelopteria gastrodes (Meek, 1873)	M
Crassostrea soleniscus (Meek, 1871)	B
Pleuriocardia pauperculum (Meek, 1871)	M
Dentonia leveretti (Cragin, 1893)	B
Corbula sp.	B-M

GASTROPODA

Craginia coalvillensis (Meek, 1873)	B
Levicerithium funicula (Meek, 1873)	B
Gyrodes conradi (Meek, 1876)	M
Fusus gabbi (Meek, 1873)	M

B = brackish
M = shallow marine